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MEGALIOCRINUS, A NEW CAMERATE CRINOID GENUS FROM THE MORROW SERIES OF NORTHEASTERN OKLAHOMA

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ABSTRACT

Camerate crinoids almost disappeared in North America at the close of the Osage epoch, early Mississippian, but several kinds have been described from Permian rocks of Timor and Sicily. Pennsylvanian strata have yielded only a few specimens of *Acrocrinus* and columnals of platycrinitids. A new genus and species of camerates, named *Megaliocrinus aplatus*, are here described from the Morrow series, early Pennsylvanian, of northeastern Oklahoma. The new genus is grouped with *Paragaricocrinus* Yakovlev, from the Permian of Sicily, and *Wannerocrinus* Marez Oyens, from the Permian of Timor, in a new family, the Paragaricocrinidae. Evidence is offered to show that the crinoids of this family were derived from the Periechocrinitidae or from unspecialized Desmidocrinidae, which are offshoots of the Periechocrinitidae.

INTRODUCTION

The occurrence of any camerate crinoid in rocks younger than Mississippian is worthy of note. The great camerate crinoid stocks largely became extinct before the close of the early Mississippian Osage epoch. In the late Mississippian Chester beds, camerates are represented only by a few rather diminutive holdovers of old stocks, and these are common only at a few horizons. Excepting a single genus,—*Acrocrinus,*—and elliptical columnals that are inferred to belong to platycrinitids, no camerate crinoids have been reported from Pennsylvanian or Permian rocks of North America nor from Upper Carboniferous strata in other parts of the world. On the other hand, several kinds of camerates, represented by a considerable aggregate number of specimens, occur in Permian deposits of Timor. The genera and species from this source that have been described by Wanner (1916, 1924, 1937) and Marez Oyens (1940) amply prove the persistence of some camerate crinoid stocks nearly to the close of Paleozoic time. One genus of camerates is known from Middle Permian beds of Sicily (Yakovlev, 1934). Although the Permian camerate crinoids bear resemblance to earlier genera and have structures that indicate origin in known earlier families, they reveal significant evolutionary change from ancestral forms. The marine formations that were deposited on the several continents during the middle and late parts of Carboniferous time should yield many camerate crinoids eventually, and the stages of evolution shown by these fossils should serve to establish definite connections between the Permian forms and their early Carboniferous progenitors.

Specimens of a new camerate crinoid recently discovered in beds of the Morrow series, of early Pennsylvanian age, near Muskogee in eastern Oklahoma, throw considerable light on the evolution of one group of Late Paleozoic crinoids. These fossils, which are named *Megaliocrinus aplatus*, n. gen., n. sp., resemble species of *Megistocrinus* Owen and Shumard (1852) from Devonian and Missis-

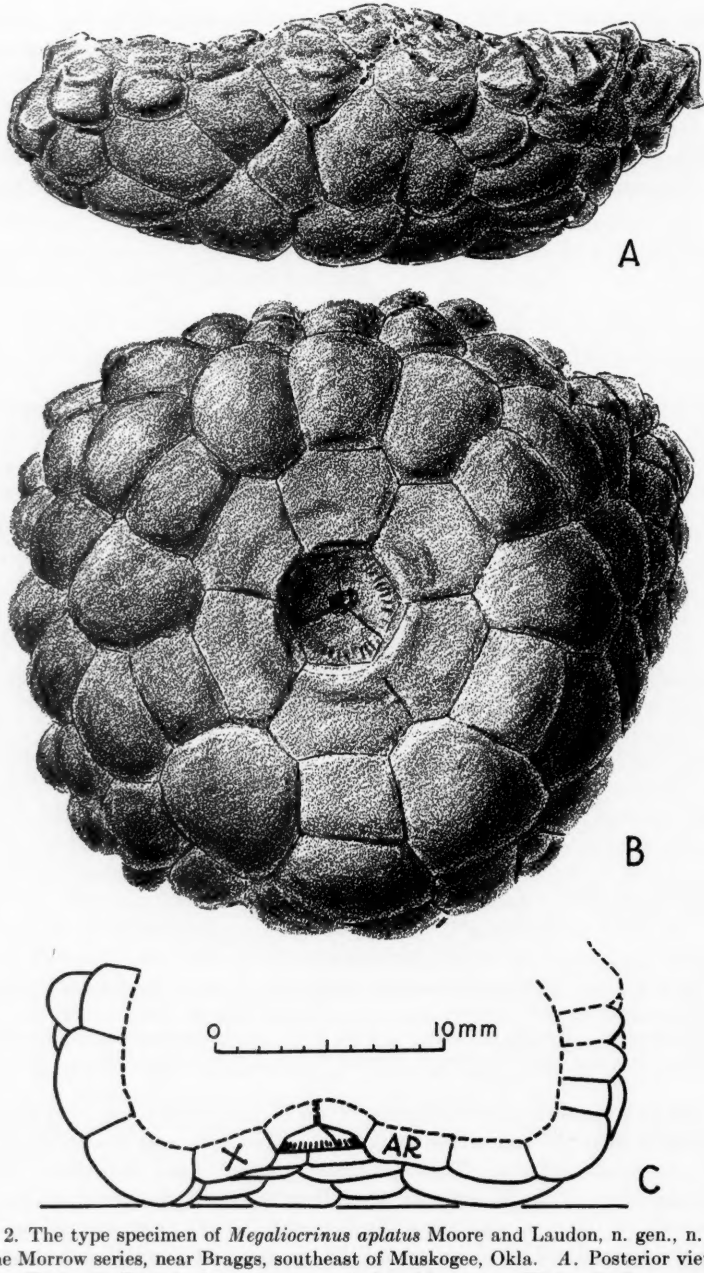

FIG. 2. The type specimen of *Megaliocrinus aplatus* Moore and Laudon, n. gen., n. sp., from the Morrow series, near Braggs, southeast of Muskogee, Okla. *A*. Posterior view of the cup, X3.5. *B*. Dorsal view of cup, posterior side at top, X3.5. *C*. Cross section through X and anterior ray, showing shape and height of basal concavity.

rays appear to be axillary and the arrangement of succeeding BrBr is regular. The TBr_1 plates of the outer parts of each ray are axillary but the inner ones are not. This plan gives rise to six arms in a ray. A single large IBr_1 occurs in each regular interray, followed by 2 or 3 smaller plates. In the posterior interray there are 3 large plates next above X and these are followed above by 3 smaller plates. None of the IBrBr are confluent with plates of the tegmen, in so far as can be determined (Fig. 3). The surface of the plates is slightly but distinctly uneven, and faint tubercles are discernible in some areas. The sutures between plates outside of the R circlet are very strongly impressed.

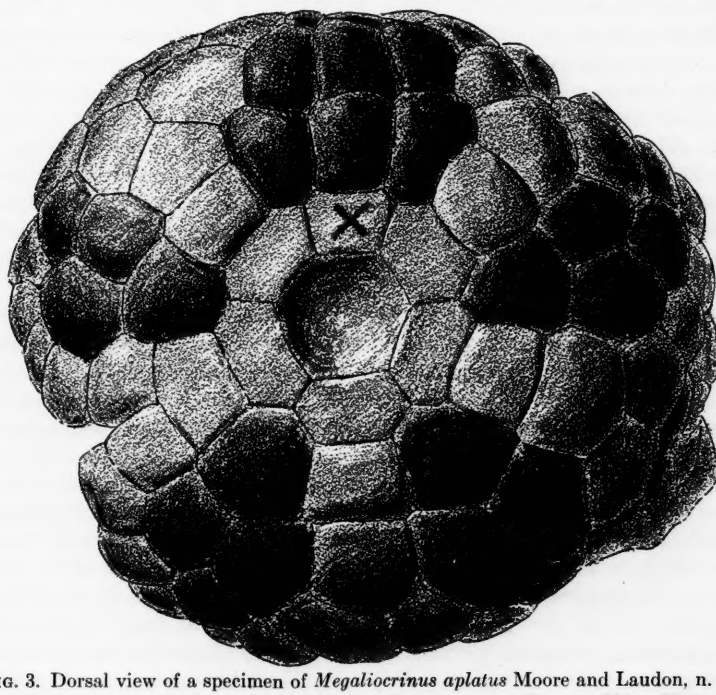

FIG. 3. Dorsal view of a specimen of *Megaliocrinus aplatus* Moore and Laudon, n. gen., n. sp., from the same horizon and locality as the type, near Braggs, Okla., X3.5. The IBrBr are dark and the X plate is indicated. The plates of this specimen lying outside of the RR are less bulbous than those of the type.

Measurements of the type and of another dorsal cup are respectively as follows: Greatest width, 32.5 mm., 31.5 mm.; height, 10 mm., 9 mm.; diameter of B circlet, 5 mm., 4.5 mm.; diameter of R circlet, 13 mm., 11 mm.; height of basal concavity, 3.5 mm., 2 +mm.

Discussion.—This new species differs widely in general appearance and structure of the cup from all other known Pennsylvanian crinoids. It can be separated from species of *Paragaricocrinus* and *Wannerocrinus*, from the Permian, on the basis of its relatively lower cup and the presence of three plates in the circlet next above X, instead of two. It is easily distinguishable from species of

Megistocrinus because the arms of this genus are grouped and the PBr_1 is hexagonal or pentagonal, whereas the arms of *Megaliocrinus aplatus* are not grouped and the PBr_1 plates are quadrangular.

Occurrence.—Limestone in the Morrow series, lower Pennsylvanian (Upper Carboniferous); at spillway below Greenleaf Lake, near center of sec. 10, T. 13 N., R. 20 E., southeast of Braggs, Okla.

Type.—Specimen (University of Kansas no. 73853), collected by Lowell R. Laudon.

RELATIONSHIPS OF MEGALIOCRINUS

The structure of the lower portion of the cup of *Megaliocrinus* is almost identical to that of *Megistocrinus*, which is characterized by its flattened base, containing three equal BB in a concavity, and surrounding these, a circlet of 6 hexagonal plates, of which 5 are RR and the remaining one is anal X. *Megistocrinus* differs from *Megaliocrinus* in the rounded globular form of its cup and large number of IBrBr (Fig. 4*E, F*). *Megistocrinus* has all of the fundamental characters of the Periechocrinitidae, in which family it is classed, but it is actually a specialized form that diverges widely from the primitive early periechocrinitid structure. The Periechocrinitidae are characterized by three equal BB, the RR in contact except at the anal side, X followed by three plates in the next circlet, the IBr_1 plates small and the PBr_1 plates hexagonal. The widely expanded truncate globular cup of *Megistocrinus*, with its unusually well developed IBrBr and anal area, differs greatly from the conical cup of *Periechocrinites* (Fig. 4*D*) and *Saccocrinus*. The only significant departures in structure of *Megaliocrinus* from *Megistocrinus* are the quadrangular PBr_1 plates and the unusually large IBr_1 plates of *Megaliocrinus*.

Early species of the Periechocrinitidae reflect many of the primitive characters of the Tanaocrinidae, from which they were evolved. In primitive camerate crinoids, the ray plates are well formed and generally strongly arched, many of them having a median ridge. The IBrBr are small and irregular in the archaic forms. The first step in evolution of the IBr plates is development of regularly polygonal outlines, but these plates are still small. The stage represented by small, regularly polygonal IBrBr is seen both in the Tanaocrinidae and in early forms of the Periechocrinitidae. As long as the IBrBr remain small, the PBr_1 plates are hexagonal or many-sided, not quadrangular. Inasmuch as the PBr_1 plates are hexagonal and the IBr_1 plates are small in all members of the Periechocrinitidae, the structure of the cup in this family is considered to be relatively primitive.

A family that may be recognized definitely as derived from the Periechocrinitidae comprises the genera grouped under the name Desmidocrinidae. Members of this family are like the periechocrinitids in having three equal BB, the RR in contact except at the anal side, and X followed by three plates in the next circlet. They differ in having a larger IBr_1 that is displaced upward so as to give the PBr_1 a quadrangular form. This tendency of the IBrBr to diminish in number and to shift upward persists in the evolution of almost all camerate crinoids throughout their history. Finally, the IBrBr are eliminated from the cup.

The dorsal cup of *Megaliocrinus* has the general shape and main structural features of *Megistocrinus*, which, as already noted, belongs to the Periechocrinitidae. The quadrangular PBr_1 and large IBr_1 plates of *Megaliocrinus*, however, are characters foreign to the Periechocrinitidae. They belong to the Desmidocrinidae, among which *Agaricocrinites* is the only genus that resembles *Megaliocrinus*. It is pertinent to inquire whether the new genus called *Megaliocrinus* originated from the Desmidocrinidae, through a form like *Agaricocrinites*, or directly from the Periechocrinitidae, through a form like *Megistocrinus*.

Agaricocrinites (Fig. 4, *A–C*) is characterized by a flattened or concave base. It has three equal BB, the RR in contact except at the anal side, X followed by three plates in the next circlet, PBr_1 quadrangular in most species, IBr_1 large, arms directed laterally from large conspicuous oval facets and strongly grouped, and the anal vent located on a rounded, more or less inflated tegmen. *Agaricocrinites* is specialized in various ways, notably in the peculiarly modified large oval arm facets (Fig. 4*A*) and prominent grouping of the arms. It differs greatly from *Megaliocrinus* in these features and we conclude that the Morrow crinoid cannot be interpreted reasonably as a descendant of *Agaricocrinites*. It could only have come from an unknown less specialized ancestor of *Agaricocrinites*.

In order to develop *Megaliocrinus* out of a form like *Megistocrinus* it is necessary merely to decrease the number of IBrBr, increase the size of the IBr_1 plates and, as accompanying or resultant change, produce four-sided PBr_1 plates. These are expectable changes because they are seen to be the normal evolutionary trend in various camerate stocks and they persist through all of Paleozoic time. *Megaliocrinus* differs importantly from *Megistocrinus*, as it does from *Agaricocrinites*, in having ungrouped arms. *Megistocrinus* and *Agaricocrinites* have grouped arms. The fixed BrBr of *Megaliocrinus* are in lateral contact at the arm bases, except at the anal side where a single thin plate lies between the fixed BrBr, connecting the anal area with tegmen plates. This development of laterally joined arm bases that separate the reduced IBr areas from the tegmen is a recognized evolutionary specialization among some camerate stocks.

The structure of the lower portion of the cup of *Megaliocrinus* differs from that of *Paragaricocrinus* and *Wannerocrinus* only in the nature of the anal interradius (Fig. 5, *A–F*). In both Permian genera, X is followed by two plates in the next circlet, instead of three. Reduction of the number of plates in the anal interradius and their displacement upward in the cup are also normal evolutionary trends in camerate crinoids and, therefore, they are to be expected in forms like *Paragaricocrinus* and *Wannerocrinus*. Characters that are common to *Megaliocrinus* and these two Permian genera include the concavity of the base and the low rounded form of the cup, the quadrangular form of the PBr_1 plates, the small number of IBrBr in each interray, and the absence of contact between the IBrBr and plates of the tegmen. The possession of these characters and the occurrence of the three designated genera in rocks that are much younger than those containing representatives of the Periechocrinitidae and Desmidocrinidae give basis for recognition of the new family that is named

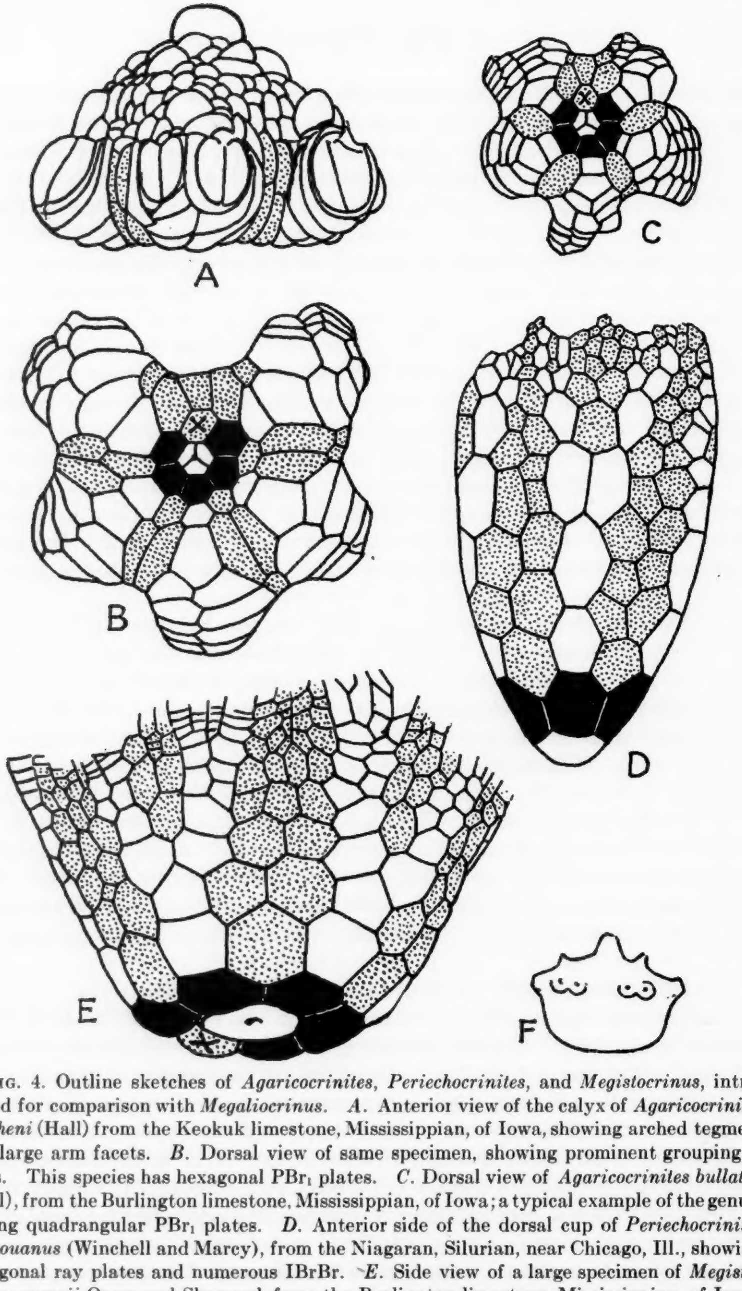

FIG. 4. Outline sketches of *Agaricocrinites*, *Periechocrinites*, and *Megistocrinus*, introduced for comparison with *Megaliocrinus*. *A*. Anterioı view of the calyx of *Agaricocrinites wortheni* (Hall) from the Keokuk limestone, Mississippian, of Iowa, showing arched tegmen, and large arm facets. *B*. Dorsal view of same specimen, showing prominent grouping of arms. This species has hexagonal PBr_1 plates. *C*. Dorsal view of *Agaricocrinites bullatus* (Hall), from the Burlington limestone, Mississippian, of Iowa; a typical example of the genus, having quadrangular PBr_1 plates. *D*. Anterior side of the dorsal cup of *Periechocrinites marcouanus* (Winchell and Marcy), from the Niagaran, Silurian, near Chicago, Ill., showing hexagonal ray plates and numerous IBrBr. *E*. Side view of a large specimen of *Megistocrinus evansii* Owen and Shumard, from the Burlington limestone, Mississippian, of Iowa. *F*. Outline of calyx of *Megistocrinus depressus* Hall, from the Hamilton group, Upper Devonian, of New York. All figures natural size, (*A–E* after Wachsmuth and Springer, *F*, after Goldring). Radials solid black, interbrachials stippled.

Paragaricocrinidae. We judge that this family was developed out of the Periechocrinitidae, either as a line that was entirely separate from the Desmidocrinidae, running parallel to it in evolutionary trend, or as a branch from an early desmidocrinid, not now known, that was not specialized in the direction leading to *Agaricocrinites*. In our opinion, the name *Paragaricocrinus* is unfortunate in

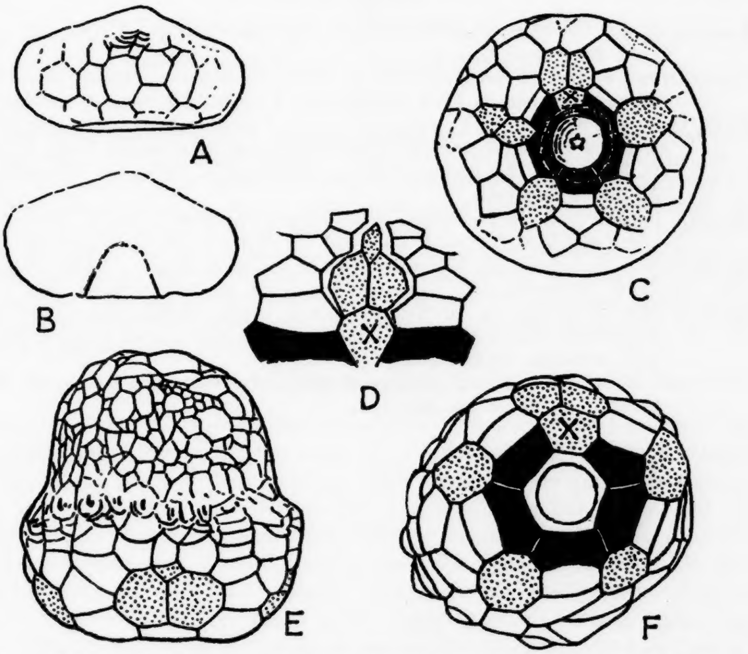

FIG. 5. Outline sketches of *Paragaricocrinus* and *Wannerocrinus*. *A*. Side view of *Paragaricocrinus mediterraneus* Yakovlev, from the Permian of Sicily. *B*. Outline of cross section, showing approximate depth and nature of the central concavity. *C*. Same, in dorsal view, posterior side at top. *D*. Plates of the posterior interradius and parts of adjoining rays in *Wannerocrinus glans* Marez Oyens, from the Permian of Timor, showing the two plates next above X. *E*. Side view of the type specimen of *Wannerocrinus glans*. *F*. Dorsal view of same, the posterior side at top. All figures (except *D*) natural size (*A–C*, after Yakovlev; *D–F*, after Marez Oyens). Radials solid black, interbrachials stippled.

that this genus seems not to be a descendant of *Agaricocrinites*, or directly related to it, but rather only a distant cousin.

The family is named from *Paragaricocrinus* because it is the first one of the group of three to be recognized, and because of a measure of doubt as to whether *Wannerocrinus* may prove to be valid. Comparison of the illustrations and descriptions that are given by Yakovlev (1934) and Marez Oyens (1940) for *Paragaricocrinus* and *Wannerocrinus* reveals only a few grounds for distinction. These may be significant or they may not. Marez Oyens seems not to have

known of *Paragaricocrinus* at the time of his publication of *Wannerocrinus*, for he does not mention Yakovlev's genus,—an omission that is hardly understandable if he was acquainted with it. The work of Marez Oyens on crinoids from Timor shows keen observation, clarity of description, and, like that of Wanner, is altogether admirable.

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METACATILLOCRINUS, A NEW INADUNATE CRINOID GENUS FROM PENNSYLVANIAN ROCKS OF OKLAHOMA

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ABSTRACT

A new genus, *Metacatillocrinus*, is described from the Altamont limestone, upper Des Moines series, from the vicinity of Tulsa, Oklahoma. The genus is characterized by the presence of two very large radials that bear numerous arms and three small radials that bear single arms. Thus, in general plan it corresponds to *Catillocrinus* Shumard and belongs to the subfamily Catillocrininae of the family Allagecrinidae. The form of the cup is very unlike that of *Catillocrinus*, however, being strikingly similar to some specialized catillocrinids from the Permian of Timor. It differs from the latter in the arrangement of arms. The new genus is especially distinguished by the relative breadth of the right posterior radial and broad, slightly elevated facet for the basal plate of the anal tube. Genotype, *Metacatillocrinus bulbosus*, n. sp.

INTRODUCTION

Crinoids of the monocyclic inadunate family Allagecrinidae Carpenter and Etheridge (1881) are among the most oddly specialized of this whole class of invertebrates. Most of the genera are characterized by the presence of two or more unbranched arms joined directly to individual radial plates, and the number of arms borne by a single radial may be as many as 30. In this feature of the arms and facets of the radials to which the arms are attached, the allagecrinids differ from all other crinoids except the Anamesocrinidae Goldring (1923), which comprises the single genus *Anamesocrinus* Goldring. The characters and classification of this group of crinoids have been discussed by Springer (1923), Wanner (1937), and Moore (1940), and it is unnecessary here to review these relationships.

First among crinoids of this group to be recognized in North America were relatively large cups called *Catillocrinus tennesseeae* Shumard (1866), from lower Mississippian rocks of Kentucky and Tennessee. Subsequently, three other species of *Catillocrinus* were recognized. These are named *C. wachsmuthi* (Meek and Worthen) (1866), *C. turbinatus* Springer (1923), and *C. shumardi* Springer (1923). All are from rocks of lower Mississippian (Osage) age in Tennessee, Kentucky, Iowa, and Indiana. These crinoids have low bowl-shaped or truncate cone-shaped dorsal cups, and are characterized by the great enlargement of two of the radials (LPR and AR) (Moore and Laudon, 1941), which bear numerous arms. Each of the other three RR bear a single arm, but the left shoulder of the RPR is elevated in the form of a process for attachment of the lowest plate (X) of an anal tube. The total number of arms in adult specimens belonging to *Catillocrinus* is reported to range from 20 to 58 (Springer, 1923).

Two other *Catillocrinus*-like genera that have been described from rocks in North America are *Eucatillocrinus* and *Allocatillocrinus*. The first genus is represented by a single species, *E. bradleyi* (Meek and Worthen) (1873), from lower Mississippian rocks in Indiana. *Eucatillocrinus* has a moderately high truncate cone-shaped cup in which two radials are much enlarged and bear numerous arms. The genus differs from *Catillocrinus* in the lack of an elevated process on the RPR for attachment of X. *Allocatillocrinus* occurs (1) in upper Mississippian (Chester) beds of Illinois, Indiana, and Alabama, where it is represented by the genotype species *A. carpenteri* (Wachsmuth) (1882), (2) in upper Lower Carboniferous beds of Scotland (Wright, 1933, 1939), and (3) in lower Pennsylvanian formations of Oklahoma where it is represented by *A. morrowensis* (Strimple) (1940), and *A. rotundus* Moore (1940). Species of *Allocatillocrinus* are readily separated from the other genera that have been mentioned by the presence of three relatively large multiple-arm-bearing radials.

Distinction between crinoids of the Allagecrinidae that have only two enlarged multiple-arm-bearing radials (subfamily Catillocrininae) and those having three or more such plates (subfamily Allagecrininae) is thought to have important phylogenetic and classificatory significance (Moore, 1940). The Catillocrininae contain *Mycocrinus* Schultze (1866), from Middle Devonian rocks of Germany; *Catillocrinus* Shumard (1866) and *Eucatillocrinus* Springer (1923), from lower Mississippian rocks of North America; and *Paracatillocrinus* Wanner (1916), from the Permian of Timor. The Allagecrininae, which, excepting some microscopic cups, comprise forms having three or more multiple-armed radials, include *Allagecrinus* Carpenter and Etheridge (1881), from Lower Carboniferous to Permian strata of Europe, North America, and Timor; *Wrightocrinus* Moore (1940), from the Lower Carboniferous of Scotland and Permian of Timor; *Allocatillocrinus* Wanner (1937), from the Lower Carboniferous of North America and Scotland, and Upper Carboniferous of North America; and *Neocatillocrinus* Wanner (1937), *Xenocatillocrinus* Wanner (1937) and *Isocatillocrinus* Wanner (1937), all from the Permian of Timor.

The discovery of a very well-preserved complete dorsal cup of an allagecrinid that differs from any previously observed type is interesting from the standpoint of light that may be thrown on the nature of evolutionary changes in this group of crinoids. Clearly, the new crinoid belongs close to *Catillocrinus*, because it has only two multiple-arm-bearing radials. The fact that it comes from Pennsylvanian rocks in which no representatives of the Catillocrininae have been found previously (although numerous examples of *Allagecrinus* and *Allocatillocrinus* have been obtained from them), extends the range of known occurrence of the Catillocrininae. It serves partly to fill the gap between the early Mississippian *Catillocrinus* and the Permian *Paracatillocrinus*. The specimen mentioned was found by Harrell L. Strimple at an outcrop of shaly beds belonging to the Altamont limestone near the top of the Marmaton group, Des Moines series, at the southeast edge of Tulsa, Oklahoma. This horizon is about 1,200 feet stratigraphically above the Morrow beds in the vicinity of Muskogee, Okla., that have yielded numerous specimens of *Allocatillocrinus*. The crinoid from

the Altamont beds is described as a new genus and species called *Metacatillocrinus bulbosus*.

Family Allagecrinidae Carpenter and Etheridge (1881)

Subfamily Catillocrininae Moore (1940)

Genus Metacatillocrinus, n. gen.

The dorsal cup is low and asymmetrical, expanding rapidly upward. The plane of the arm facets is distinctly inclined to that of the base, the greatest elevation being on the side of the RPR. The B circlet consists of a very low flat disk that is little, if any, larger than the stem impression, but it is visible in side view of the cup. No sutures between the B plates are discernible, and accordingly this circlet seems to be fused solidly. There are five RR, which are very unequal. The AR and LPR are greatly enlarged, together forming about 80 per cent of the circumference of the cup at the summit. The RPR is nearly half as large as the AR and LPR; the LAR and RAR are very much reduced, especially at the top. Numerous arm facets occur on the AR and LPR but only one each is seen on the RPR, LAR, and RAR. The left part of the RPR is elevated and bears a broad flattened attachment for an anal tube. Distal parts of the RR are greatly thickened and the body cavity is much constricted. The arms are unknown. The stem impression is elliptical; it is elongated in the plane of the RAR and LAR.

Genotype.—*M. bulbosus*, n. sp., Altamont limestone, near Tulsa, Okla.

Discussion.—The inequality in size of the RR and the distribution of arm facets as observed in the new crinoid from the Altamont limestone correspond in part with characters of *Mycocrinus*, *Catillocrinus*, *Eucatillocrinus*, and *Paracatillocrinus*. The very diminutive size of the RAR in *Metacatillocrinus bulbosus* is a point of difference which sets this crinoid sharply apart from *Allocatillocrinus* and other allagecrinid genera. Plainly, *Metacatillocrinus* belongs to the Catillocrininae.

The form of the dorsal cup of *Metacatillocrinus* differs from that of any of the Devonian or Carboniferous representatives of the Catillocrininae, but the abrupt lateral expansion of the upper part of the cup and the obliquity of the summit plane are essentially the same as in *Paracatillocrinus*, *Isocatillocrinus* and *Xenocatillocrinus*, from the Permian of Timor. Resemblance of *Metacatillocrinus* to *Mycocrinus*, *Catillocrinus* and *Eucatillocrinus* is seen in the reduced size of the RPR, RAR and LAR, and in the arrangement of facets for the arms and the lowest anal tube plate. Also, the relative widths of the RR at their proximal margins are similar in the genera mentioned and these differ from the characters seen in *Paracatillocrinus*. The distal extremities of the RAR and LAR are notably narrower than the proximal widths of these plates in all of the genera mentioned, except *Paracatillocrinus*. In contrast to all of them, the RPR of *Metacatillocrinus* becomes strongly widened upward from the base. This feature is observed in no other genus of the Catillocrininae. The left part of the RPR of *Metacatillocrinus* is elevated, but the raised portion does not have the form of a process for the attachment of X, as in *Mycocrinus* and *Catillocrinus*. This

peculiarity definitely separates the new genus from *Eucatillocrinus*. The RPR of *Paracatillocrinus* bears a single facet which is regarded as the attachment for an arm; no anal tube seems to be present reaching to the outer margin of the RPR. This and other characters sharply distinguish *Metacatillocrinus* from *Paracatillocrinus*. The obliquity of the axis and ellipticity of the stem impression of these crinoids are notably similar.

Special comment on characters of the RPR in allagecrinid genera, including the catillocrinids, is pertinent. It is well recognized that in forms such as *Allagecrinus, Catillocrinus, Allocatillocrinus*, and others, the left side of the RPR supports an armlike structure that can be distinguished positively as an anal tube. Unequivocal evidence that the structure is an anal tube is given by Springer (1923), Wright (1933), Moore (1940), and other writers, and yet resemblance of the anal tube to an arm is amazingly great, particularly in certain ones of these crinoids. The facet that supports the anal tube may bear marks of articulation and a pit denoting position of the axial nerve canal, just like those of the true arm facets. Consequently, examination of the ventral side of a dorsal cup may not show any positive signs of the presence or absence of an anal tube. *Paracatillocrinus, Neocatillocrinus*, and *Isocatillocrinus* have been interpreted by Wanner (1916, 1937) as lacking an anal tube. This may be true of *Paracatillocrinus*, and it was accepted in the case of the other two genera by Moore in 1940 (pp. 90, 91). Careful study of the figured specimens of *Neocatillocrinus* and *Isocatillocrinus* (Wanner, 1937, pl. 14, figs. 1–13; Marez Oyens, 1940, pl. 3, figs. 6, 7) seems, however, to indicate that the facet at the left edge of the summit of the RPR is actually the place of attachment of an anal tube. This is suggested by slight differences of the inferred anal and true arm facets that match observed slight differences in corresponding facets of *Allocatillocrinus, Allagecrinus* and other genera known to have an anal tube. Marez Oyens (1940, p. 318) recognizes the facet just indicated in *Neocatillocrinus* as almost surely that of an anal tube, but according to his view, the anal tube of *Isocatillocrinus* was inserted in a notch between the RPR and LPR. Nevertheless it is seen that the leftmost facet of the RPR differs very considerably from the others of this plate.

The combination of characters that serves to distinguish *Metacatillocrinus* from allied genera include the inclined summit plane of the cup, elliptical form of the stem impression, and the characters of the RPR, especially its broad distal surface and the slightly elevated facet for the attachment of an anal tube. The new genus can hardly be regarded as a transition form connecting *Catillocrinus* and *Paracatillocrinus* because the RPR is relatively much more prominent in the new genus than in either of the others mentioned. The form of the dorsal cup is much more strongly suggestive of the Permian genera than those of the Carboniferous and older genera.

Metacatillocrinus bulbosus, n. sp.

Text figures 1–6

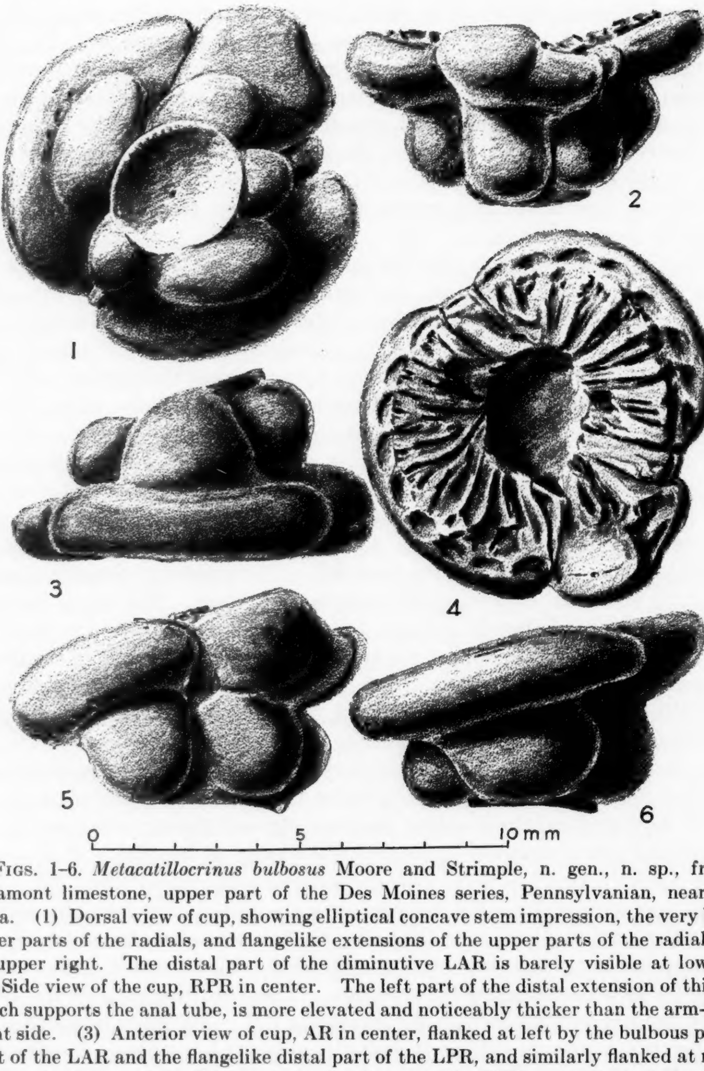
The general nature of this species is described in characterization of the genus. Features of specific importance may be regarded as including the detailed form of the plates and the smooth surface.

The basal circlet is delimited by plainly marked sutures at the margin along parts of the periphery, but these sutures are obscure in some places. The area of the elliptical stem impression is mostly smooth and distinctly concave (Fig. 1), the depth of the depression amounting to about 0.5 mm. The margin of the impression bears extremely short crenellae. A minute round lumen occurs at the center of the area. Outside of the stem impression the surface is subvertical to the basal-radial sutures, and this part of the basal circlet is plainly visible in side view of the cup, except at points where the bulbous RR reach to the basal plane of the cup.

The RR have an extremely peculiar shape in that the lower portions are expanded in balloon-like bulges and the upper parts are also greatly expanded (Figs. 1–3, 5, 6), the swollen distal parts of the LPR, AR and RPR being strikingly broad and thick flanges. A deep constriction separates the lower and upper parts of each R. These indentations are so marked that careful examination was made during study of the specimen in order to determine whether some of the plates might not be divided by transverse sutures in the manner of some RR of *Anamesocrinus* Goldring (1923). No such transverse sutures are present in *Metacatillocrinus*. The periphery of the summit is notably indented at the points where the RAR and LAR occur, inasmuch as these plates extend outward less than the other RR (Figs. 1, 4). Also, their distal expansions are somewhat thinner than those of the large RR. The sutures at the side margins of the LAR and RAR curve slightly, converging upward. The suture between the RPR and LPR is nearly straight, but runs obliquely upward toward the right. The asymmetry of form of the large RR is clearly indicated in the dorsal and lateral views of the cup (Figs. 1–3, 5, 6). The under side of the right flange of the LPR bears a row of faint pits (Figs. 1, 5), but similar pits are not observed on the other RR and accordingly these may be adventitious features.

The summit portions of the RR are very broad and nearly even, defining a plane that deviates strongly from a position parallel to the basal plane of the cup. If the specimen is held so that the basal plane of the cup is horizontal, the summit plane slopes downward from its highest point at the middle of the outer edge of the RPR to a low point near the anterior extremity of the LPR. The sloping upper surface of the RR is occupied by the deep narrow facets for attachment of the arms and anal tube (Fig. 4). Shallow pits along the outer edge of the RR are the outer ligament areas of each facet. These readily serve to show the number of arms belonging to each plate. There are nine arms on the LPR, eight on the AR and one each on the remaining RR. The inner ligament areas of the facets are grooves, defined laterally by elongate low ridges. Small round pits marking the position of axial canal openings are visible on the transverse ridges between the outer and inner ligament areas of some facets but not on others. The facets of the LAR and RAR are the same in size as those on the two large RR, but the arm facet on the right shoulder of the RPR is nearly twice as large as the others.

The very broad and nearly smooth elevated portion on the left part of the RPR is clearly different from any of the arm facets in that there is no depression near the outer margin corresponding to the outer ligament area of the arm facets,



FIGS. 1–6. *Metacatillocrinus bulbosus* Moore and Strimple, n. gen., n. sp., from the Altamont limestone, upper part of the Des Moines series, Pennsylvanian, near Tulsa, Okla. (1) Dorsal view of cup, showing elliptical concave stem impression, the very bulbous lower parts of the radials, and flangelike extensions of the upper parts of the radials; RPR at upper right. The distal part of the diminutive LAR is barely visible at lower left. (2) Side view of the cup, RPR in center. The left part of the distal extension of this plate, which supports the anal tube, is more elevated and noticeably thicker than the arm-bearing right side. (3) Anterior view of cup, AR in center, flanked at left by the bulbous proximal part of the LAR and the flangelike distal part of the LPR, and similarly flanked at right by the proximal part of the RAR and the distal part of the RPR. (4) Ventral view of cup, the wide facet for attachment of the anal tube occurring at right of lower center; it is distinguished from the other facets by the breadth and smoothness of the outer part of the area. (5) Posterior view of cup, the suture between the LPR and RPR nearly vertical in center of figure. (6) View of cup from the side of the LPR, showing strong inclination of the summit to the basal plane of the cup. (Camera lucide drawings by R. C. Moore.)

and the inner part of the area is a groove that becomes constricted between prominent ridges. Resemblance to an arm facet is seen in the presence of a

shallow round pit like that of the axial canals of the arm facets and in the lateral ridges on the inner side of the anal facet. The position of this articular surface in relation to the whole cup and the irregularity in outline of the body cavity, which is extended outward in the position of the left side of the RPR, are characters that plainly identify the posterior side of the cup (Marez Oyens, 1940, p. 316; Moore, 1940, p. 91). Characters of the facet give support to the inference that the anal tube of *Metacatillocrinus* is a robust armlike structure.

Measurements of the type and only known specimen of *Metacatillocrinus bulbosus* are: Greatest width of cup, 9 mm.; greatest height, 5.2 mm., to summit of RPR; height on low side, 2.7 mm., at anterior edge of LPR; diameter of stem impression 3.8 mm. by 3.2 mm.; width of body cavity, 3 mm.

Occurrence.—Upper part of the Altamont limestone, Marmaton group, Des Moines series, Pennsylvanian (Upper Carboniferous), in road cut on eastward extension of 31st Street, at southeast edge of Tulsa, Okla.

Type.—The holotype, collected by Harrell L. Strimple, is to be deposited in the Springer Collection, U. S. National Museum.

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BLASTOIDS FROM MIDDLE PENNSYLVANIAN ROCKS OF OKLAHOMA

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ABSTRACT

No blastoids younger than the fairly common remains of *Pentremites* in the early Pennsylvanian Morrow strata have previously been reported in North America. Several genera and species of blastoids have been described from Permian rocks of Timor, Australia, the U. S. S. R., and Sicily, however. Recently two complete calices representing a new species of codasterid blastoid have been found in the Hogshooter limestone at Ramona, Okla. The horizon of these fossils belongs in the middle part of the Missouri series, which comprises the upper middle part of the Pennsylvanian (Upper Carboniferous) rocks of the midcontinent region. The specimens are determined to belong to the genus *Paracodaster* Yakovlev (1940), described on the basis of a single fossil from Lower Permian beds of the Urals region of Russia, and the new species is named *Paracodaster dotti*.

INTRODUCTION

Remains of blastoids are known to occur in Paleozoic formations of North America ranging in age from Chazyan (Ordovician) to Morrow (early Pennsylvanian). The oldest described species is *Blastoidocrinus carchariaedens* Billings (1859), from the Chazy limestone near Montreal and in New York, and the youngest are two species, *Pentremites rusticus* Hambach (1903) and *P. angustus* Hambach (1903), from "Chester limestone of Washington County, Arkansas." As stated by Mather (1915, p. 100), Hambach's specimens undoubtedly came from the Brentwood limestone, which was termed the "Pentremital limestone" by the early Arkansas Geological Survey and which was thought to be of Chester age. The Brentwood is now a well recognized division of the Morrow strata in northwestern Arkansas and adjacent parts of northeastern Oklahoma and is known to be of early Pennsylvanian age. It corresponds to middle Pottsville deposits of the eastern states, as indicated by the close similarity of the rich floras obtained from shale just above the Brentwood and from the horizon of the Sewell coal in the central Appalachian region. Calices of *Pentremites* are exceptionally common at some outcrops of the Brentwood limestone and it is an item of incidental interest that the Morrow blastoids have striking superficial resemblance to the Chazyan forms (Billings, 1859, text-figs. 5–8, p. 20).

Between the occurrence of blastoids just noted there are many deposits that contain remains of these pelmatozoans, although only in upper Mississippian strata are the genera and species relatively numerous and individual specimens extraordinarily abundant at many places. Blastoids are useful guide fossils in the systems that contain them.

The known stratigraphic range of blastoids in other continents exceeds that of North America, inasmuch as some also occur in Ordovician rocks and others

are reported from beds as young as Permian. The blastoid-bearing Permian deposits are located in Russia, Sicily, Timor, and Australia. The Timor assemblage of Permian blastoids is much the richest in variety and numbers among those yet discovered in beds younger than Mississippian. It contains 15 described genera and nearly three dozen species (Wanner, 1924, 1931). Two additional genera have been reported from the Lower Permian of the U. S. S. R. (Yakovlev, 1932, 1940) and another new genus has recently been reported from Australia (Brown, 1941).

OCCURRENCE OF NEW BLASTOIDS IN OKLAHOMA

A small outcrop of limestone and calcareous shale at the north edge of the town of Ramona, in the southern part of Washington County, Oklahoma, has yielded some dorsal cups of inadunate crinoids and fragmental crinoidal remains, along with other marine invertebrates. The specimens of blastoids that are described in this paper were found by the junior author in the course of numerous collecting trips to this locality. The first discovered specimen, which is selected as the type of the new species that it represents, was obtained in 1940, and the second, which is also a complete calyx, was collected in 1941. Evidently, these fossils are rare. No other blastoids have been found by either of us in post-Morrow Pennsylvanian rocks during several years of field work in northeastern Oklahoma and southern Kansas, and we know of none obtained by other collectors.

The stratigraphic horizon of the blastoid-bearing beds is at or very near the top of the Hogshooter limestone, which is one of the most persistent limestones in the Pennsylvanian section of the northern midcontinent region. South of Ramona, which is about 15 miles due south of Bartlesville and 25 miles east of north from Tulsa, the Hogshooter limestone has been mapped for a distance of 100 miles or more, and northeastward it is traced into central Iowa. In Kansas, this limestone is known as the Winterset member of the Dennis limestone. In Missouri and Iowa, it is designated simply as the Winterset limestone. Its type locality is in Iowa. The Hogshooter limestone,—using the Oklahoma name,—is classed as a part of the Skiatook group, which comprises the lower and main division of the Missouri series in Oklahoma and southern Kansas. The blastoid horizon at the top of the limestone lies about 450 feet above the disconformity that marks the base of the Missouri series and it occurs 500 feet below the disconformity that is defined as the boundary between the Missouri and overlying Virgil series. Thus, the bed under consideration is almost in the middle of the Missouri series as measured in the latitude of Ramona. The thickness of strata belonging to the Des Moines series, next below the Missouri, in the area near Ramona is about 1,000 feet, and that of the Morrow beds in this latitude less than 100 feet. The thickness of the Virgil series west of Ramona is slightly over 1,300 feet. These figures indicate that the Hogshooter is about 1,500 feet above the base of the Pennsylvanian section and 1,800 feet below the Permian.

DESCRIPTION OF THE BLASTOIDS

The blastoids from the Hogshooter limestone are flattened specimens of nearly equal size, the one that is selected as type being 15 mm. long and 11.5 mm. wide, and the other having a length of 14 mm. and a greatest width of 12.5 mm. These measurements do not exactly indicate the dimensions of the un-

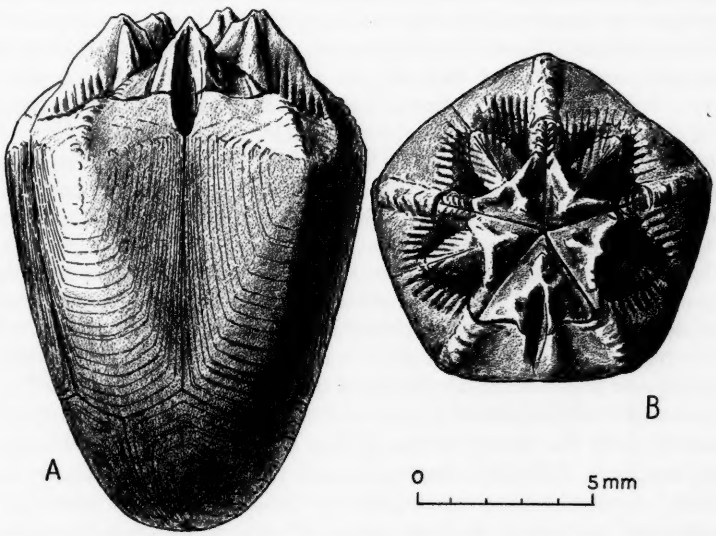

FIG. 1. *Paracodaster dotti* Moore and Strimple, n. sp., from the top of the Hogshooter limestone, Missouri series, upper middle Pennsylvanian, from Ramona, Washington County, in northeastern Oklahoma. Restorations by R. C. Moore, based on camera lucida drawings of the compressed but complete calyx that is designated as type. *A*. Posterior view, showing the rounded base and elongate radials, which bear concentric lines and ridges, and indicating the strongly crested character of the deltoids. The anal aperture is located partly on the posterior deltoid and partly between the summits of the posterior radials; it is bordered laterally and adorally by a prominent V-shaped ridge that culminates in a sharp peak. *B*. Ventral view, showing the rounded median elevations on the distal part of the radials, the narrow straight ambulacral grooves and side plates bordering them in three of the rays, and the crested nature of the deltoids. Hydrospire folds occur in eight areas along edges of the deltoids and indenting the margins of the radials, except opposite the posterior deltoid.

distorted calices, of course. The accompanying illustrations (Fig. 1*A*, *B*) are restorations based on study of the least disturbed plates and they indicate as accurately as possible the undistorted character of the type. The drawings were prepared before the second specimen was discovered, but examination of this fossil has revealed no essential differences in characters as determined from the camera lucida drawings and other work on the first specimen. The summit,

base, and all of the radials are shown clearly by both specimens, and the plates are mostly not displaced at all along sutures. They retain their relative positions.

The base consists of two large plates and a smaller one, which is located in the right anterior interray. The position of the sutures between the basal plates is shown by the pattern of concentrically disposed growth lines or fine ornamental ridges on the plates and by observation of the sutures themselves. It is pertinent to mention the surface markings of the plates, because one could easily misconstrue a fracture as representing a suture if the break in continuity of the plate surface chanced to occur in a position that might be occupied by a suture. Judging from the outline of the compressed calices and from the shape of the least disturbed basal plates, we conclude that the original form of this circlet is that of an evenly rounded bowl having shallow scallops at its upper edge. The width of the bowl at the summit is almost twice its height. The concentric markings on the plates of the bowl are very prominent in the case of the type specimen but less marked on the other example.

The five radial plates that enclose the higher part of the body cavity are elongate spade-shaped. They are widest along a line that lies well below the distal margin and that marks an abrupt inward bending of the summit portion of each plate. The maximum width of a radial, measured to include curvature, is slightly less than 6 mm. The length of the outwardly directed face of a radial is 7.5 mm. and of the upwardly directed part about 2.3 mm., a total of 9.8 mm. measured along the surface in the midline of the plate. Concentric lines or ridges are clearly defined on the outer face of the radials but not on the summit portion. A moderately sharp angulation separates the outer area from the summit area, and along the line of this inflection the growth line ridges are commonly accented by slight thickenings. Faint angulations are seen on the outer face of the radials, running from the proximal margin at the angles and midline of the plates to the centrally located projection near the summit. The distal parts of the radials bear a median ridge that is rounded and marked on the top by cross wrinkles or low tubercles. Narrow slits indent the margins of the radials that adjoin the tegmen, but they are lacking at the middle of the distal edge of each plate and on parts of the posterior radials that touch the posterior deltoid. These slits mark the position of hydrospire folds. There are about seven of these folds in each of the eight slit-bearing areas. The posterior side of the calyx is defined by a prominent opening that indents one of the deltoids deeply and extends between two of the radials to the line of angulation dividing the summit and lateral areas of these plates. This is the anal vent.

The tegmen is mostly covered by the five large deltoids, parts of which are elevated in rather strong crests. The highest point on each of these plates is nearly at its center, and from the peaks formed here, comblike ridges extend along the midline of the plates outward in the direction of the radials and inward in the direction of the mouth. Also, spurs extend laterally from the peaks of the crests, running nearly at right angles toward the ambulacral furrows.

The pattern of the main ridge and spurs on each deltoid, except the posterior, has approximately the form of an arrow. The slopes facing the radials bear hydrospire folds, except on the posterior deltoid, which differs in the arcuate form of a part of its crest that borders the anal vent and in the smooth unslitted nature of its lateral slopes. The posterior deltoid is not divided by a transverse suture, as in some Permian blastoids. The mouth is a centrally located very small pentagonal opening. The ambulacral grooves that diverge from it are narrow and sharply marked. They are bordered by the steeply sloping borders of the deltoids. Near the LAR, AR, and RAR, the ambulacra are flanked on each side by a row of short side plates, but these are not observed along the ambulacra that join the posterior radials.

GENERIC ASSIGNMENT AND DESIGNATION OF NEW SPECIES

The structural characters that have been described from study of the Ramona blastoids clearly indicate that they belong to the long-ranging family Codasteridae Etheridge and Carpenter (1886). Indeed, the Oklahoma specimens are not very far removed from the genus *Codaster* McCoy (1849), which is known to be represented by species of Silurian, Devonian, and Mississippian age. The form of the calyx of *Codaster* is bell-shaped to ovoid and the ambulacral region is a subhorizontal area occupying the summit, as in the blastoids under discussion. The anal vent of *Codaster* is a relatively large laterally placed opening. The hydrospire slits border the ambulacra except on the side that bears the anal aperture, and the interambulacra may be elevated in crests. Our specimens differ from *Codaster* in the absence of side plates along parts of the ambulacra that lie near the mouth and, so far as can be seen, on any portion of the two posterior ambulacra. Also, the hydrospire folds do not extend more than a short distance onto the radial plates of the two Oklahoma blastoids. There is some doubt whether the observed indentations are, indeed, true slits. The hydrospires of *Codaster* reach deeply into the radials in the area close to the ambulacra so as to form broad lozenge-like slitted tracts on adjoining parts of radials and deltoids. Most, if not all of the hydrospire slits seem to be borne by the deltoids in the case of the Hogshooter specimens, but because of the deformation of the calices and the presence of open spaces between deltoids and radials, where the delicate hydrospire structure has been broken away, this conclusion is not entirely certain. One of the specimens that shows the distal margin of two radials plainly has only slight corrugations along the edge of the plates. The other calyx has more deeply marked indentations that match the hydrospire folds in position but these indentations seem to be marginal and surficial. Certainly they are not elongate slits, as in *Codaster*. Lastly, we may observe that the anal vent of *Codaster* lies wholly within the area of the posterior deltoid, but in the blastoids here described the aperture deeply indents the radial circlet.

None of the long-known genera of the Codasteridae, except *Codaster*, are at all similar to the Pennsylvanian forms from Oklahoma. These genera, *Orophocrinus* von Seebach (1864), *Phaenoschisma* Etheridge and Carpenter (1882), and

Cryptoschisma Etheridge and Carpenter (1886), may be dismissed from present notice. In 1924, Wanner described nine new genera that were assigned to the Codasteridae and in 1931 he added a tenth new genus. Yakovlev (1933, 1940) has introduced two more codasterid genera, and recently Brown (1941) has defined still another genus. These 13 genera are all described from Permian rocks of Timor, Russia, and Australia. Thus, the known stratigraphic range of the family has been extended and its development in very late Paleozoic rocks is shown to be surprisingly large.

Comparison of the Oklahoma blastoids with illustrations of the several described Permian genera fails to show more than a distant resemblance, except in the case of Yakovlev's genera named *Sagittoblastus* and *Paracodaster*. As in our specimens, the posterior deltoid of the two genera from Russia is not divided into an upper and lower plate, the parts of the ambulacra near the mouth are open narrow grooves that are not bordered by side plates, and the interambulacral areas are raised in the form of arrow-shaped crests. *Sagittoblastus* has only 3 or 4 hydrospire folds in each area and it shows petaloid groups of side plates along the posterior ambulacra, which are not seen in our specimens. In so far as can be determined from Yakovlev's figures and description, these side plates are lacking on the posterior ambulacra of *Paracodaster*. The anal aperture of *Sagittoblastus* and *Paracodaster* indents the radial circlet, but seemingly not so deeply as in our specimens. *Paracodaster* has 6 or 7 hydrospire folds in each of 8 groups, placed in the interambulacral area except on the posterior side. Yakovlev states that the hydrospire slits are open on the deltoids but closed on the parts that extend to the borders of the radials. Furrows and intervening ridges that correspond to hydrospire folds in direction and position are seen on the radials but open slits are not observed. These characters of the tegminal surface in *Paracodaster* correspond closely with those of the blastoids here studied. In view of other essential identities, such as the ovoid shape of the calyx and proportions of its different parts, it seems proper to refer our specimens to *Paracodaster*.

Genus PARACODASTER Yakovlev, 1940

Paracodaster dotti, n. sp.

Text figure 1

The blastoids that have been described clearly represent a new species. Some of the American and European species of *Codaster* from Lower Carboniferous rocks have a form that is generally similar to the outline of the calyx of the Oklahoma specimens, but they are deemed to be generically distinct. Only one species of *Paracodaster* has been described and it is based on a single specimen. This is named *P. miloradovitchi* (Yakovlev, 1940, p. 887) and by monotypy it is the genotype of *Paracodaster*. The specimen was found in Permian strata of the Petschora coal basin, U. S. S. R. The outline of the calyx in ventral view is subpentagonal and closely resembles our Fig. 1*B*. In side view, however, the shape of the Russian blastoid is seen to be decidedly rotund, the height, which

is 20 mm., being only a little greater than the maximum width, which is 16 mm. The base is truncate, not evenly rounded.

The new species that is here reported from Upper Carboniferous strata of North America is named *Paracodaster dotti*, in recognition of contributions to geology, especially in northeastern Oklahoma, that have been made by the State Geologist of Oklahoma, Robert H. Dott.

Occurrence.—Top of the Hogshooter limestone (equivalent to Winterset limestone of other northern midcontinent states), Skiatook group, Missouri series, Pennsylvanian (Upper Carboniferous); west of U. S. highway no. 75 at north edge of Ramona, Washington County, Oklahoma.

Type.—The type and additional studied specimen, collected by Harrell L. Strimple, are to be deposited in the U. S. National Museum.

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A NEW SPECIES OF SYNBATHOCRINUS FROM MISSISSIPPIAN ROCKS OF TEXAS, WITH DESCRIPTION OF ONTOGENY

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CONTENTS

ABSTRACT

Adult dorsal cups and numerous immature calices of a new species of *Synbathocrinus*, discovered in the Chappel limestone of Osage age, early Mississippian, in central Texas are described and named *S. texasensis*. Chief interest attaches to the young specimens, which range from cups having a height of less than 1 mm. and lacking arm facets to those only a little smaller than adults and having five arm facets. The young specimens have a circlet of oral plates in position above the radials. The arms are not developed simultaneously on the different rays but in a sequence, the anterior arm being the last to appear. The very young calices of *Synbathocrinus* bear such close resemblance to *Kallimorphocrinus* that their true generic nature would doubtless be mistaken if it were not for the presence of progressively more advanced forms that connect them definitely with typical *Synbathocrinus*. Specimens showing early growth stages of this genus have not been described previously.

The erroneously reported stratigraphic range of *Synbathocrinus*, from Silurian to Permian, is corrected by rejection of cited occurrences of the genus in Silurian rocks and by assignment of Permian synbathocrinids to *Taidocrinus*. The emended range of *Synbathocrinus* is Middle Devonian to Middle Mississippian.

INTRODUCTION

The primary purpose of this paper is to record observations that throw light on growth stages of the monocyclic inadunate crinoid *Synbathocrinus*. Studies

of the ontogeny of fossil crinoids are almost entirely lacking in the literature, mainly because specimens representing several growth stages of any given species, especially the very young stages, have not been discovered. Many immature crinoids are doubtless present in all large collections, but commonly they are sporadic examples of different species rather than suites representing successive stages in the development of a single species. In some cases juvenile individuals have been misinterpreted as adult forms and have been described as new species. Incidental purposes of the present paper are to give description of a new species of *Synbathocrinus*, to extend knowledge of the early Mississippian marine fossils belonging to the central Texas region, and to make correction of the reported stratigraphic range of the genus *Synbathocrinus*.

Occurrence of the crinoids.—The specimens that are to be described were found by us in April, 1940, in a small area of Chappel limestone cropping out on the south side of Colorado River about one-fourth mile east of the highway bridge at Marble Falls, Burnet County, Texas. The Marble Falls limestone, of early Pennsylvanian age, is excellently exposed in the bluffs and floor of the valley at this place, which is the type locality of the Marble Falls formation, and many geologists have visited the outcrops in order to study the section. The succession of Marble Falls beds was measured and described by the senior author (Plummer and Moore, 1922) in 1918. He reported, as did Paige (1912), that the Marble Falls limestone here lies disconformably on the Ellenburger limestone, of early Ordovician age. Locally in this area, the Marble Falls does rest directly on the Ellenburger, but it is now known that on the north side of the Colorado River at Marble Falls a few feet of upper Mississippian Barnett shale intervenes at the base of the Marble Falls formation. Barnett beds have not been observed on the opposite side of the river, but here also the Marble Falls limestone is separated in most places from the Ellenburger by a small thickness of Mississippian deposits. The intervening beds here belong to the Chappel limestone, which is of Osage age (Girty, 1926). Their presence was first recognized by the junior author of this paper in the course of field studies of the Marble Falls type section, which were planned for preparation of a Master's thesis in geology at the University of Kansas. Discovery of the Chappel beds in the Marble Falls area was confirmed by Mr. F. B. Plummer, of the University of Texas, for whom Mr. Ewers was working as assistant, and later by Mr. Moore. The Chappel formation consists of impure crinoidal limestone and greenish calcareous shale, its thickness in this area ranging from a feather edge to a maximum of about 7 feet. The average thickness of the Chappel beds near Marble Falls is only a couple of feet and the maximum thickness noted represents very local fillings of depressions in the subjacent Ellenburger limestone. The fossil crinoids were collected from shaly Chappel beds in such a pocket at a point about one-fourth mile east of the highway, near the site of an old dam, and about half way up the steep bare rock valley side south of the river.

Acknowledgments.—Mr. F. B. Plummer, of the Bureau of Economic Geology, University of Texas, has been engaged for the last few years in detailed studies of the Carboniferous stratigraphy of the Llano region in central Texas. He has shown that the subdivisions and interrelations of the Mississippian and Pennsyl-

vania deposits of this area vary notably from place to place and he is preparing a comprehensive report on the complex features of Carboniferous stratigraphy and structure of the area. We are greatly indebted to Mr. Plummer for his freely given approval of the partially independent stratigraphic study of Mr. Ewers on the Marble Falls type section and of the paleontologic work that is reported in this paper. Also Mr. Plummer has aided by work in the field on several occasions.

DESCRIPTION OF NEW SPECIES

Family SYNBATHOCRINIDAE S. A. Miller, 1889

Genus SYNBATHOCRINUS Phillips, 1836

Synbathocrinus texasensis, n. sp.

Text figures 1–27

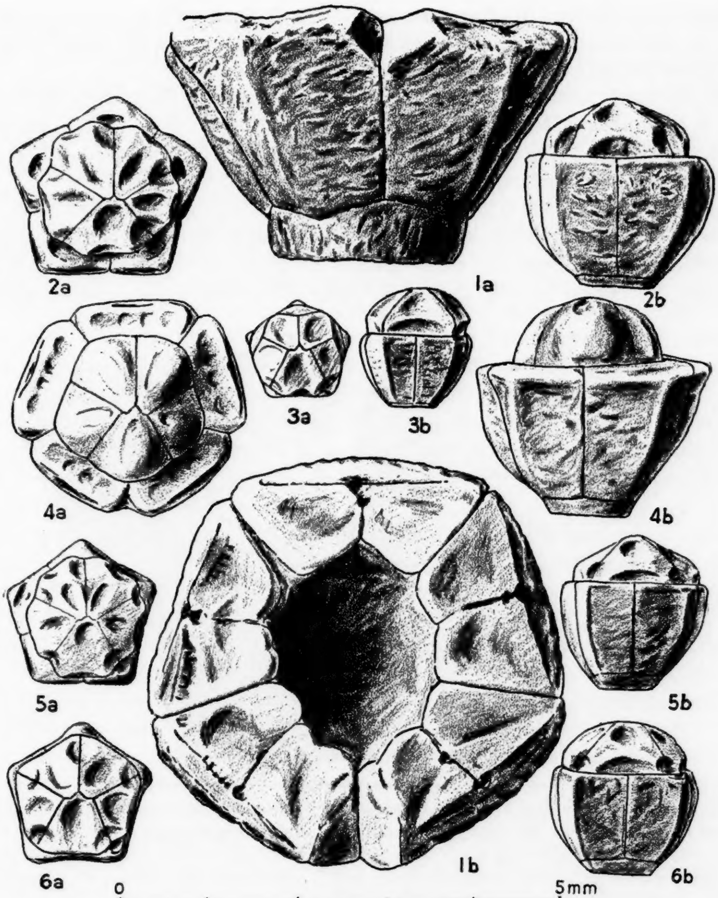
Description of this species is based on four dorsal cups that are considered to represent adult growth stages and on more than 100 specimens that are identified as immature examples of the species. It is desirable to describe these two groups separately and then to submit evidence that the small calices are actually young individuals belonging to the same species as the larger dorsal cups.

Adult specimens.—The dorsal cups are truncate cone-shaped, the height being slightly more than one-half of the greatest width. The basal circlet comprises two large plates and a small one, the latter located in the left anterior interray.

The proximal part of the BB, which is covered by the stem impression, is gently concave; the median part, which lies outside of the stem area, is tangent to the basal plane of the cup; and the distal part extends upward subvertically. The height of this circlet is about one-fourth of the total height of the cup.

The RR slope upward at an angle of about 55 degrees and the midline of each R is marked by a fairly prominent keel. The facets are broad and gently concave. They bear a straight transverse ridge or sharp-crested angulation that extends from the outer corners of the facets to a shallow oval pit located halfway between the corners. This pit marks the position of the axial canal. The part of the facet lying outside of the transverse ridge slopes outward at an angle of about 45 degrees; this part is slightly hollowed or nearly flat and featureless. The inner part of the facet, which is much larger than the outer, slopes outward at an angle of about 20 degrees; it is gently concave and is bisected by a narrow intermuscular furrow. Shallow oblique furrows are observed on some of the facets extending from the outer corners toward the center. The inner margins of the facets are not abruptly elevated, as in some species of *Synbathocrinus*, but they are indented by a shallow intermuscular notch.

The position of the anal X plate is shown by a strongly marked beveling of the left upper corner of the RPR and a somewhat similar beveling of the right upper corner of the LPR. The slope of the beveled surface on the RPR and the width of this surface are noticeably unlike those on the LPR, the more gentle slope and greater width being on the RPR. This indicates that the X plate is borne by the RPR but it crowds against the LPR so as to make the oblique truncation of its corner that is observed.



FIGS. 1–6. Adult and immature specimens of *Synbathocrinus texasensis*, n. sp., from the Chappel limestone, Lower Mississippian, near Marble Falls, Texas. **1*a*, *b*,** Posterior and ventral view of the dorsal cup of an adult specimen (Univ. Kansas no. 60852B). **2*a*, *b*,** Ventral and posterior views of specimen (no. 60852Y) having five narrow arm facets. **3*a*, *b*,** Same views of a very young specimen (no. 60852AC) that lacks arm facets. **4*a*, *b*,** Same views of a calyx (no. 60852E) that is nearing maturity, characterized by wide arm facets. **5*a*, *b*,** Same views of an immature specimen (no. 60852X) having only two arm facets, on the RPR and LAR, respectively. **6*a*, *b*,** Same views of an immature specimen (no. 60852AA) having a single arm facet, on the RPR. (Camera lucida drawings by R. C. Moore).

The body cavity of the dorsal cup is relatively constricted. The outline of the cavity at the level of the R facets is roughly elliptical, the transverse width being distinctly less than that of the antero-posterior axis.

The surface of the dorsal cup is marked by irregular ridges and nodes that are prominent in some specimens, giving the plates a rugose appearance, and less

prominent but distinct in other specimens. On the basal plates the trend of the ridges is approximately at right angles to the distal margin of the plates, and on the radials it is subparallel or oblique to the distal margin.

Measurements of the type (Fig. 7) and of specimens A, B, and C, are as follows, in millimeters: Height of dorsal cup, type 4.0, A 6.5, B 2.7, C 2.1; greatest width, type 6.9, A 11, B 4.7, C 4.0; diameter of B circlet, type 3.7, A 6.3, B 2.2, C 1.9; diameter of stem impression, type 2.3, A 3.3, B 1.6, C 1.5.

Immature specimens.—The crinoids from the Chappel limestone that are identified as immature individuals belonging to *Synbathocrinus texasensis* may be divided conveniently into three groups for purposes of description. These comprise (1) calices having five wide facets that form a prominent shelf-like

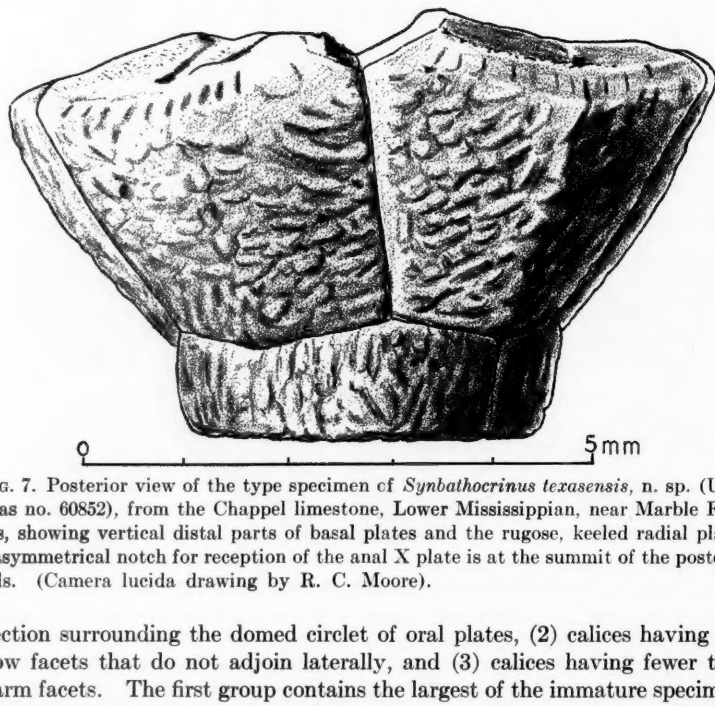


FIG. 7. Posterior view of the type specimen of *Synbathocrinus texasensis*, n. sp. (Univ. Kansas no. 60852), from the Chappel limestone, Lower Mississippian, near Marble Falls, Texas, showing vertical distal parts of basal plates and the rugose, keeled radial plates. The asymmetrical notch for reception of the anal X plate is at the summit of the posterior radials. (Camera lucida drawing by R. C. Moore).

projection surrounding the domed circlet of oral plates, (2) calices having five narrow facets that do not adjoin laterally, and (3) calices having fewer than five arm facets. The first group contains the largest of the immature specimens and the third group contains the smallest specimens. There is no sharp dividing line between the groups and it is believed that they are parts of a growth series.

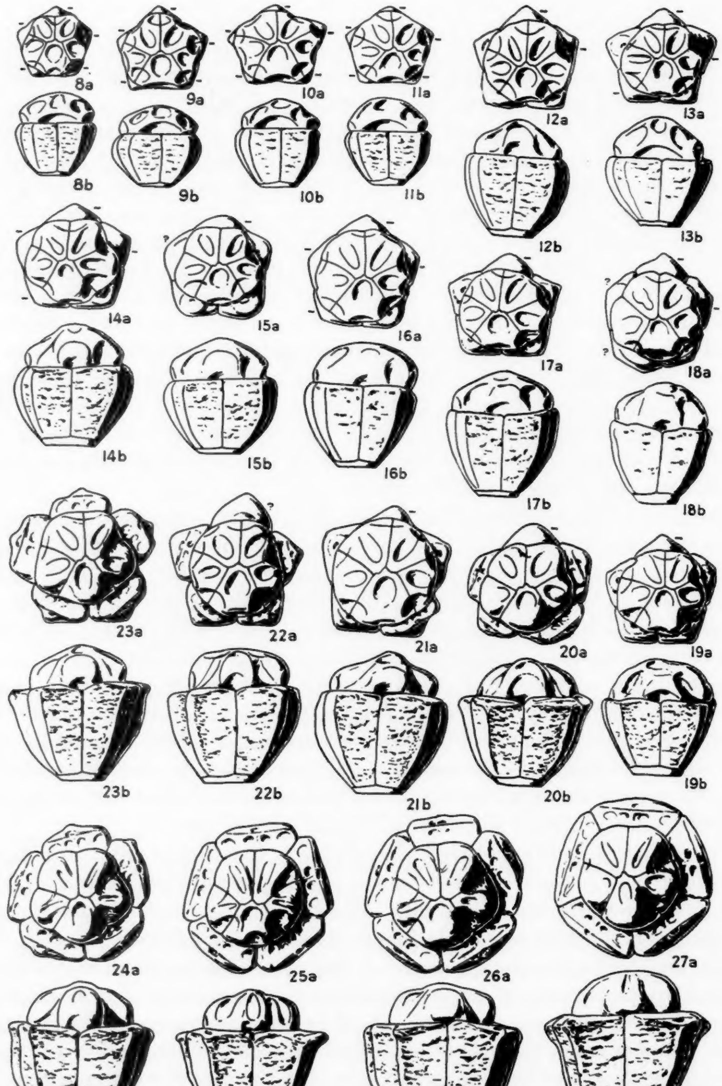
(1) The wide faceted young specimens are common. They comprise 25 to 30 individuals in our collection, which is about one-fourth of the total number of young *Synbathocrinus* picked out of the washings. Typical examples are illustrated in Figures 4*a*, *b*, 24*a*, *b*, 25*a*, *b*, 26*a*, *b*, and 27*a*, *b*. The B circlet is low and in all characters it closely resembles the BB of adult specimens of *Synbathocrinus texasensis*. The proximal area is gently concave and the distal

part rises very steeply. Several individuals clearly show the two large and one small B plates, the latter being located uniformly in the left anterior interray. The sutures are obscure on the B circlets of a few specimens, but none having more than 3 BB has been observed. The RR are subequal and each bears a prominent median ridge or keel. The proximal part of these plates commonly slopes upward less steeply than the distal part, which gives a bowl-shaped outline. Some specimens have evenly sloping RR and in this respect more closely resemble the adult cups of *S. texasensis*. The facets are equal in width to the greatest transverse dimension of the RR, and adjoining facets are separated only by a slight depression along the suture line. The length of the facets is about one third of their width. A straight, sharply marked angulation crosses each facet transversely, dividing it into a narrow outer area and a relatively broad inner area. The former slopes outward more steeply than the latter and is more nearly plane. A small pit representing position of the axial canal occurs on or adjoining the angulation that separates the outer from the inner area. Well-preserved specimens show a broad shallow depression in the inner facet area and within this are two centrally located deeper hollows and two faintly marked laterally placed hollows.

The posterior side of the calices is identified by the arrangement of plates in the oral circlet, the posterior O being the only unpaired plate. In some specimens there is a distinct notch between the posterior RR, but it is not prominent and there is no indication on any of the observed calices that an anal plate was attached to the RPR. Some specimens have no more sharply marked indentation between the posterior RR than between any of the others, and if the OO were lacking it would probably be impossible to determine the correct orientation of the cup reliably. The height of the O circlet is about one third of that of the dorsal cup. The proximal part of these plates is subvertical and the distal part nearly horizontal. The median area of each plate is commonly arched so that the sutures between them lie in depressions. An elongate depression more or less distinctly indents the rounded summit area of each O.

The surface decoration of these dorsal cups is like that of adult specimens of *Synbathocrinus texasensis* except for the average smaller size of the markings. In proportion to the size of the cups, however, the rugose ornamentation of the immature specimens is essentially identical to that of adult cups.

(2) The group of young specimens of *Synbathocrinus texasensis* that is characterized by the presence of five narrow facets is illustrated by Figures 2*a*, *b*, 22*a*, *b*, and 23*a*, *b*. Such specimens are about half as numerous as the wide-faceted cups. In side view, the calices having narrow facets do not differ perceptibly from those that have been described, except in the case of some cups that have very short as well as narrow facets. The narrow-faceted cups are slightly smaller than the wide-faceted specimens. In ventral view, the outline of the narrow-faceted cups is so unlike that of the wide-faceted forms that one might well be sceptical of their asserted specific identity. The strongly marked angles of the pentagonal outline are located on midlines of the rays in the group here under consideration (Fig. 2*a*), whereas the angles of the rounded pentagons belonging



FIGS. 8–27. Ventral and posterior views of immature specimens of *Synbathocrinus texasensis*, n. sp., from the Chappel limestone, Lower Mississippian, near Marble Falls, Texas, showing variation in shape, size, and development of arm facets. Minus signs (−)

to the wide-faceted cups are interradial (Figs. 4*a*, 25*a*, 26*a*, 27*a*). An intermediate stage is illustrated in Figure 23*a*, and taking account of all features, there is little reason to question the conclusion that the narrow facets are gradually widened so as to blunt the radial points of the narrow-faceted forms by filling in the interradial areas until the angles of the pentagonal outline are shifted.

The OO of the narrow-faceted calices are similar to those of the wide-faceted types in general proportions and in the outline of the dome, but the elongate depressions along their midlines are more accentuated. Strongly marked concavities are present next to the facets, in the position of the interoral sutures. Surface markings of the plates correspond to those of the larger specimens described.

(3) The third group of immature specimens is numerically predominant in the assemblage studied by us. They range in size from calices that are fully as large as examples of the second group to individuals that are less than half as high and wide as those already described. A few calices that are thought to belong in this group have a height of only 0.35 to 0.5 mm, which is one sixth to one fifth of the height of the largest examples of this group.

Figures 17*a*, *b*, 19*a*, *b*, 20*a*, *b*, and 21*a*, *b* show specimens that bear four arm facets. In each of these and several other examples of four-faceted cups, the anterior R is smoothly rounded distally, showing no sign of the beginning of a facet. Commonly the RPR facet is distinctly wider than any of the others (Fig. 21*a*). Specimen V (Fig. 15*a*, *b*) has three fairly well defined facets and possibly a fourth. In this case the doubtful facet is the one belonging to the LAR, which is normally the second R to develop an arm (Moore, 1940, p. 125; 1940a, p. 576).

No specimens having three well defined facets and two unfaceted RR have been observed in the Chappel collection, although they may be present among

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adjacent to the summits of radials indicate absence of an arm facet. 8*a*, *b*, A very young armless calyx (Univ. Kansas no. 60852AC). 9*a*, *b*, A similar specimen (no. 60852AB) that is slightly wider and lower than average. 10*a*, *b*, Another armless specimen (no. 60852AI). 11*a*, *b*, An armless specimen (no. 60852AL). 12*a*, *b*, A specimen (no. 60852Z) having small but distinct facets on the RPR and LAR, and an incipient facet on the LPR. 13*a*, *b*, A calyx (no. 60852AG) having only two arm facets, on the RPR and LAR. 14*a*, *b*, A relatively large immature specimen (no. 60852P) that has an arm facet only on the RPR. 15*a*, *b*, A specimen (no. 60852V) that lacks a facet on the AR and possibly on the LAR. 16*a*, *b*, A large immature calyx (no. 60852T) having an arm facet only on the RPR. 17*a*, *b*, A specimen (no. 60852H) that lacks a facet only on the AR. 18*a*, *b*, A specimen (no. 60852C) having a facet of the RPR and obscure facets on two other radials. 19*a*, *b*, A specimen (no. 60852S) having four arm facets, the AR lacking a facet. 20*a*, *b*, A specimen (no. 60852M) similar to no. 60852S but facets distinctly wider. 21*a*, *b*, A specimen (no. 60852Q) having a wide facet on the RPR, narrow facets on the LAR, RAR and LPR, and none on the AR. 22*a*, *b*, A specimen (no. 60852R) having prominent lobate radials that all bear facets, the one on the AR being incipient. 23*a*, *b*, A calyx (no. 60852O) having well developed facets on all radials but not closely adjoining. 24*a*, *b*, A specimen (no. 60852I) like no. 60852O but facets widened. 25*a*, *b*, A calyx (no. 60852H) having nearly mature characters. 26*a*, *b*, A nearly mature calyx (no. 60852N) having a distinctly bowl-shaped form. 27*a*, *b*, A typical nearly mature calyx (no. 60852J). (Camera lucida drawings by R. C. Moore).

the dozens of small calices that have not been carefully examined. Specimen Z (Figs. 12*a*, *b*) has facets on the RPR and LAR, and it shows a flattened area on the LPR that may be a facet; the RAR and AR lack facets. There may be some variation in the order of development of the facets, and it is possible that two or more facets may appear simultaneously, but study of other microcrinoids indicates that normally the RAR facet precedes development of a facet on the LPR. Specimen U (Figs. 18*a*, *b*) has two doubtful arm facets, which are located on the LAR and LPR; the RAR and AR lack facets.

Two-faceted cups are shown in Figures 5*a*, *b* and 13*a*, *b*, and they are represented by several unfigured specimens. The facet-bearing RR seem uniformly to be the RPR and LAR. The outline of the dorsal cup in ventral view is strongly pentagonal, the angles being located on the midlines of the rays. The unfaceted RR may project as far beyond the oral circlet as those having facets, but their distal part is seen to be very smoothly rounded.

Calices that show the presence of only a single arm facet are illustrated in Figures 6*a*, *b*, 14*a*, *b* and 16*a*, *b*, and additional ones are found in our collection. In each specimen, the RPR is seen to be the one that first develops a facet. It is a small concavity at the tip of the R, next to the groove between two OO.

Specimens that lack all trace of arm facets are fairly numerous in the group here discussed. They are smaller than the other calices and commonly the distal extremities of the RR barely project beyond the circlet of OO. Typical examples are illustrated in Figures 3*a*, *b*, 8*a*, *b*, 9*a*, *b*, 10*a*, *b* and 11*a*, *b*. The shape of the dorsal cup is closely similar to that of the specimens having one or more facets, and the domed O circlet is similar, except that depressions are stronger. The keeled nature of the RR and the rugose markings on the plates in all of the studied specimens are characters that support inference of their specific identity.

Evidence for identification of immature specimens.—It is pertinent to review briefly evidence indicating that the small crinoids having oral circlets in place, which have been described, belong to *Synbathocrinus texasensis.*

(1) Association together of the adult dorsal cups and of the inferred immature calices belonging to the same species is not in itself proof of their specific identity but it certainly aids in reaching conclusions on the nature of the small specimens. The adult cups of *Synbathocrinus* are the only crinoids larger than 3 mm. in width that have yet been found in the Chappel limestone, so that if any of the more diminutive Chappel crinoids represent young growth stages of megascopic forms, *Synbathocrinus* has first call for consideration.

(2) The supposed young examples of *Synbathocrinus texasensis* have dorsal cups that differ little in shape from the type and from other adult specimens of this species. This is especially true of the larger immature cups. The proportions of height to width of the dorsal cup of more than three dozen small crinoids belonging to the group under consideration are plotted in Fig. 28, including specimens G, D, and numerous others that are not designated by letter, shown farther left in the diagram. These fall on or near a straight line that, on being extended, intersects the plotted position of the type of *S. texasensis*. Specimens

A, B, and C, which are adult cups, have slightly lower height to width ratios than that indicated by the straight line on the diagram. Probably more significant than the general outline and proportions of the cup is the strongly keeled nature of the RR, both in the adult cups and in the immature specimens. These features are strongly suggestive of identity.

(3) The surface markings of the adult and immature groups are similar. Both have relatively prominent irregular grooves and ridges that tend to run subhorizontally on the RR and subvertically on the BB.

(4) Several of the inferred immature cups of *Synbathocrinus* definitely show the positon of sutures of the B circlet. These have three BB, the small plate being located in the left anterior interray. This is the same as in the adult cups. The

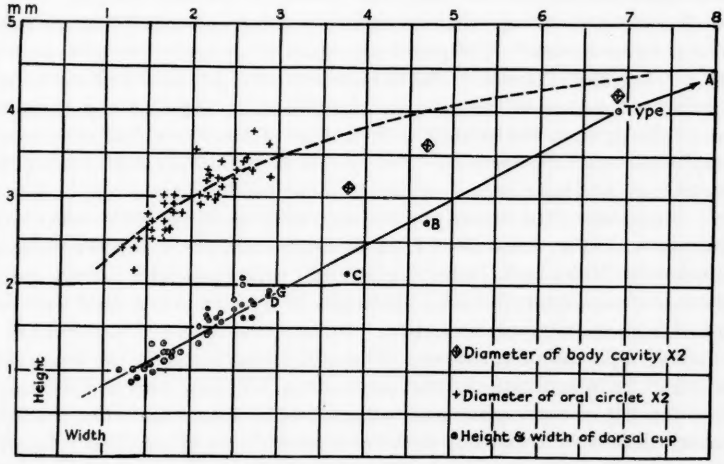

FIG. 28. Diagram showing growth stages of *Synbathocrinus texasensis*, the lower line representing the ratio of height to width of the dorsal cup, and the upper line indicating diameter of the oral circlet (X2). Symbols adjacent to upper curve are placed vertically above the plotted point of the dorsal cup height-width ratio to which they belong, and the measurements are to be read from the scale at the left.

structure of the B circlet cannot be determined definitely in the case of many of the youngest specimens, but one of these seems to have four BB. None has been observed that shows five BB, although this number would be entirely expectable in a very young *Synbathocrinus*.

(5) The oral circlet of the largest immature specimens of *Synbathocrinus texasensis*, according to our identification, attains or exceeds the diameter of the body cavity of small adult dorsal cups of this species (Fig. 28). Wachsmuth and Springer (1885, pl. 5, figs. 12–14) have illustrated a specimen of *Synbathocrinus wachsmuthi* Meek and Worthen that shows the oral circlet in position next to the inner edges of the R facets. This is the only example of observed OO in a species of *Synbathocrinus*, in so far as we are aware, and it is of interest

because of the small size of the O circlet in comparison to the width of the cup. The dome of OO does occupy the area between the edges of the RR, defined as the body cavity. Seemingly, the O circlet is a prominent feature of young individuals of *Synbathocrinus*, as of *Allagecrinus* (Wright, 1932, 1933; Moore, 1940) and *Allocatillocrinus* (Moore, 1940), but it does not keep pace with the plates of the dorsal cup in growth, and it is commonly not preserved in adult specimens. The size of the O circlet in the young *Synbathocrinus texasensis* agrees closely with estimated dimensions of this circlet, based on width of body cavity, belonging to adult specimens of this species.

The immature crinoids that have been described are readily distinguished from associated calices of similar size that are identified as belonging to *Kallimorphocrinus* (for spelling of this name see Moore, Weller and Knight, 1942, p. 257). The latter have cups that are relatively much taller and that are nearly circular in cross section. The plates are smooth. Sutures have not been observed dividing the B circlet. The OO are very abruptly raised at the margins and deeply excavated in the median areas, forming together a pattern that differs markedly from the summit of the calices of the young *Synbathocrinus*.

Comparison with other species.—Ten species of *Synbathocrinus*, coming from rocks of Osage age, have been described, although some of these may be synonymous. A number of the known species, such as *S. angularis* Miller and Gurley, *S. blairi* S. A. Miller, *S. wortheni* Hall, *S. wachsmuthi* Meek and Worthen, and *S. illinoisensis* Miller and Gurley, have dorsal cups that differ little in general proportions or size from the large specimens of *Synbathocrinus* that have been described from the Chappel formation. None of the species mentioned has the well marked differentiation between BB and RR that is seen in the Texas specimens, which have subvertical distal parts of the BB, and none has the median keels of the RR or the rugose ornamentation of *S. texasensis*. The characters just mentioned serve to distinguish the new species from all previously described forms.

Occurrence.—All of the collected specimens of *Synbathocrinus texasensis* have been obtained from an outcrop of the Chappel limestone, Osage series, Mississippian (Lower Carboniferous), on the south side of Colorado River, about one-fourth mile downstream (east) from the highway bridge at Marble Falls, Burnet County, Texas.

Type.—The type specimen is University of Kansas no. 60852. Other figured specimens are deposited in the paleontological collection of the University of Kansas.

RANGE OF SYNBATHOCRINUS

Reported Silurian to Permian occurrence.—The genotype of *Synbathocrinus* is *S. conicus* Phillips (1836), from Lower Carboniferous rocks of northern England. Numerous species have been described elsewhere from Lower Carboniferous strata, including especially the early Mississippian rocks of North America. In 1858, Hall (p. 483) described a representative of the genus (*S. matutinus*) from Upper Devonian beds of Iowa, and in 1923 additional species were de-

scribed from the Upper Devonian (Hamilton) of New York by Springer (*S. hamiltonensis*, equals *S. subtrigonalis* Goldring, which is a junior synonym) and by Goldring (1923) (*S. sulcatus*). Springer (1923, p. 29) also described a new species of *Synbathocrinus* (*S. onondaga*) from Middle Devonian limestone at Louisville, Ky. The occurrence of *Synbathocrinus* in Middle Silurian rocks of Tennessee was reported in 1909 by Wood (pp. 26, 27), who described *S. tennesseensis* Roemer, *S. granulatus* Troost, and a new species, *S. troosti* Wood, all from the Brownsport limestone of Decatur County. Bassler (1915) recorded these Silurian occurrences of *Synbathocrinus* in his bibliography of American Ordovician and Silurian fossils, but Springer in 1913 (p. 209) listed the range of *Synbathocrinus* as Devonian and Carboniferous.

Species having uncertain placement in the Carboniferous, perhaps Lower Carboniferous, possibly Upper Carboniferous, or even Permian, were described from Australia by De Koninck (1877, p. 158). In 1931, a synbathocrinid from Siberia was described by Tolmatchoff (p. 598) under the new generic name *Taidocrinus*. Strimple (1938, p. 8) described a new species, based on a single specimen found in middle Pennsylvanian rocks of northeastern Oklahoma.

The occurrence of *Synbathocrinus* in Permian rocks of Timor has been reported by Wanner (1916, 1924, 1937) on the basis of descriptions of at least half a dozen new species and varieties. These are certainly in the genetic line of *Synbathocrinus*, even though they may not be included unhesitatingly in this genus. They differ from Lower Carboniferous and Devonian species in having the anal X plate above the summit line of the RR, rather than partially entering the dorsal cup.

Accepting the assignments by Wood of Silurian crinoids to *Synbathocrinus* and by Wanner of Permian crinoids to this genus, Bassler (1938), in his index of *Paleozoic Pelmatozoa*, records the range of *Synbathocrinus* as Silurian to Permian. Actually, as indicated in the following paragraph, no reliable ground for citation of a specimen of *Synbathocrinus* older than Middle Devonian can now be given, and it seems desirable that the Permian and perhaps the Pennsylvanian reported occurrences of the genus should be changed.

Invalidity of cited occurrence of Synbathocrinus from Silurian rocks.—The record of *Synbathocrinus* in pre-Devonian formations rests solely on Wood's (1909) interpretation of specimens and labels in the Troost collection and on her interpretation of Troost's manuscript. Troost (1850) differentiated two species that he called *Synbathocrinites tennesseeae* and *Synbathocrinites granulatus*. Under the first of these names, according to Wood (1909, p. 26), he identified specimens from Middle Silurian rocks, now called Brownsport limestone, of Decatur County, Tennessee, and from Carboniferous strata at White's Creek Springs, near Nashville, Tenn. Wood recognized differences between these specimens and assigned them to two species. One was referred to *Synbathocrinus tennesseensis* Roemer and the other was described as a new species, *Synbathocrinus troosti* Wood. Both were listed as fossils of the Brownsport limestone. Wachsmuth and Springer (1886, pp. 166, 174) had recognized that Roemer's *S. tennesseensis* is really a *Pisocrinus*. Springer, in 1926 (p. 80), de-

scribed and illustrated *Pisocrinus tennesseensis* (Roemer), noting its occurrence in the Dixon and Brownsport limestones of Tennessee and the Bainbridge limestone of Missouri, and he called attention to Wood's error in designating the species as a *Synbathocrinus*. Accordingly, Troost's specimens of "*Synbathocrinites tennesseeae*" from the Silurian are not *Synbathocrinus*.

Troost's examples of "*Synbathocrinites tennesseeae*" from White's Creek Springs, which Wood described as *Synbathocrinus troosti*, are properly referred to *Synbathocrinus*, but they come from Lower Carboniferous shaly beds, not from Silurian outcrops. Supporting this assertion are the facts that (1) there are no exposed Silurian rocks close to White's Creek Springs, Tennessee; (2) a party from the University of Kansas, including the senior author of this paper, accompanied by Dr. Charles Wilson, Jr., of Vanderbilt University, in 1941 collected several typical examples of *Synbathocrinus troosti* from the early Mississippian Osage beds at White's Creek Springs; and (3) no specimen of *S. troosti* is known to have been found anywhere in Silurian rocks. The confusion in Troost's manuscript and materials and Wood's confusion in dealing with them are indicated in her comment on the horizon and locality of *Synbathocrinus robustus* (Wood, 1909, p. 28).

> The specimen (*S. robustus*) is recorded in the manuscript as from Decatur County, but it is preserved in the same way as material from White's Creek Springs, and is probably of the horizon represented at that locality. The locality label of this specimen may have been confused with that of *Symbathocrinus troosti* (*S. tennesseeae* in part) which was labeled from White's Creek Springs, while it probably came from Decatur County.

It is very safe to conclude that Wood's statement as to the horizon and locality of her types of *S. troosti*, which are given as Brownsport limestone of Decatur County, Tennessee, are entirely erroneous.

Troost's other species of *Synbathocrinus*, called *S. granulatus*, is validated by publication in Wood's (1909, p. 27) paper of Troost's original description and by illustations of his type specimen. It is recorded, without comment, as occurring in the Brownsport limestone of Decatur County. We have found *S. granulatus* in the so-called New Providence beds, of Mississippian age, at White's Creek Springs. No Silurian crinoid that could be assigned to the species has been found. This record by Wood of the stratigraphic occurrence of *S. granulatus* is also in error.

Removal of the three cited species as valid records of the occurrence of *Synbathocrinus* in Middle Silurian rocks leaves Springer's *S. onondaga*, from the Middle Devonian of Kentucky, as the oldest known occurrence of this genus.

The genus Taidocrinus Tolmatchoff.—As has been intimated, the Permian crinoids that have been classed as belonging to *Synbathocrinus* may well be considered as generically distinct. The upward shift of the anal X, which is an evolutionary trend seen in a large number of crinoid stocks, has attained a stable advanced stage in these very late Paleozoic synbathocrinids. The fact that a very few specimens have an anal that slightly indents the summit of the RR does not serve to invalidate the concept of generic delimitation of these very late

Paleozoic forms from typical *Synbathocrinus* any more than the occasional absence of anal X from the cup of *Delocrinus* signifies lack of satisfactorily clear definition of the latter genus.

We suggest that the Permian species described by Wanner do not belong to *Synbathocrinus*. The inadequacy of Tolmatchoff's (1931, p. 598, pl. 21, figs. 1–3) illustrations and description of *Taidocrinus poljenowi*, which is the genotype and only species yet assigned to *Taidocrinus*, makes uncertain whether this genus is actually a junior synonym of *Synbathocrinus* or whether it can be recognized as an independent genus, to which, conceivably the Permian species belong. *T. poljenowi* was described from "Carboniferous rocks of the Kousnetzk Basin" U. S. S. R. The anal plate of *T. poljenowi* seems not to indent the circlet of RR, and otherwise this species is closely comparable to the forms figured by Wanner. We conclude that it is desirable to separate from *Synbathocrinus* the Permian species in which the anal X plate is excluded from the cup but instead of proposing a new genus to include them, we propose to refer them tentatively to Tolmatchoff's genus.

Doubtfully assigned to *Taidocrinus* is the single described Pennsylvanian species that has been assigned to *Synbathocrinus*, which may be designated as *Taidocrinus? melba* (Strimple). The description of this species states that the anal plate is not observed to indent the R circlet, but seemingly the posterior part of the cup is not well enough preserved to permit accurate observation.

De Koninck's (1877, p. 158) "*Synbathocrinus ogivalis*", from the Carboniferous of New South Wales, has a very strange geometrical design that resembles a five-sided Corinthian capital. One may well wonder whether the specimen very closely corresponds to the illustrations. The rim of the cup of this croinoid does not bear a notch for reception of an anal plate and it is not at all like any known species of *Synbathocrinus*. Possibly it belongs to *Taidocrinus*.

Corrected range, Middle Devonian to Middle Mississippian.—Removal of post-Mississippian species from *Synbathocrinus* leaves *S. swallovi* Hall, reported from the St. Louis limestone, of Meramec age, Middle Mississippian, as the youngest recognized species of the genus. *S. onondaga* Springer, from Middle Devonian limestone of Kentucky, is the oldest occurrence of the genus that seemingly is valid. The present known range of *Synbathocrinus*, therefore, may be given as Middle Devonian to Middle Mississippian. The great majority of described species belonging to *Synbathocrinus* are early Mississippian (Lower Carboniferous). The genus has considerable value as a stratigraphic marker.

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MERCURY VAPOR LAMPS

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INTRODUCTION

One of the more important tasks of the engineer is to devise and then prepare for the manufacture of light sources. This is truly a gigantic undertaking as can be understood from the fact that about 1,250,000,000 lamps of all types and sizes were made and sold in the United States during 1941! This great number of lamps may be divided into four classes: (1) tungsten lamps, (2) fluorescent lamps, (3) gas and vapor lamps, and (4) photoflash lamps. Other divisions are, of course, possible such as large lamps and miniature lamps, photographic lamps, etc. In previous papers in this JOURNAL, the tungsten lamps (*1*), the fluorescent lamps (*2*), and the photoflash lamps (*3*) have been described, and it is the purpose of this paper to give some of the characteristics and operating conditions of the mercury vapor arc lamps.

The radiation output of the mercury vapor arcs is different from that of the tungsten lamp. The radiation from the tungsten lamp consists of a continuous spectrum while that from these vapor arc lamps for low pressure is made up of radiation concentrated at various wavelengths throughout the spectrum; and for high pressures of the mercury vapor, the radiation given by the mercury vapor arc tends to become continuous. These characteristics will be more fully described in what follows. Also, the mercury vapor arc lamps have markedly different electrical characteristics from the tungsten lamps. The tungsten filament lamp has a definite resistance which increases in a definite manner as the filament is heated by the passage of the current. Thus the tungsten lamp can be operated directly across the supply main without any special control device. Such is not the case for the mercury arc lamps. These lamps in general require special apparatus to start them and then some special equipment for their operation. This is because their resistance decreases markedly after the current has been started, that is, they will operate on a much lower voltage than that necessary to start the current through them. They have what is called a negative voltage-current relation; thus, as the current increases, the voltage necessary to maintain this current decreases, which means that the current would increase to a value that would destroy the lamp if some means were not at hand to limit it. For operating mercury arc lamps on direct current, a resistance must be in series with the lamp and power supply; and for operation on alternating current, either a resistance or a choke coil must be in series with the lamp to limit the current.

These current-limiting devices always use some power and thus reduce the

over-all efficiency of the lamp. If the makers of the lamps made all the operating equipment for these lamps, they would probably always take into consideration the power loss in the control device when giving the efficiency of the light source, but since this is not the case, lamp efficiencies are customarily given. In general, some statement is made about the necessary power loss in well designed equipment for operating these lamps.

RADIATING PROPERTIES OF MERCURY VAPOR

Mercury and tungsten, the metals most used for converting electrical energy into light and into the neighboring infrared and ultraviolet, have respectively the lowest and the highest melting and boiling points of any of the metallic elements. The reason for this contrast is that there are two diverse ways of securing satisfactory lamp life: the use of a filament which will remain solid, neither melting nor evaporating at an unduly rapid rate, and the use of a conductor which will not become solid under ordinary meteorological conditions, and will flow back to its original location when displaced. Associated with this difference in physical state, these metals show characteristic qualitative differences in the emitted radiation.

These differences are those which exist, in the political and economic sphere, between individualism and collectivism. This is not to gainsay that, in either type of lamp, the number of atoms involved in the process of radiation is unimaginably large. Nevertheless, while the atoms of a tungsten filament jostle one another so continually that no part of the radiation, distributed continuously over the region of the spectrum permitted by thermodynamic considerations, can be regarded as the product of any particular atom in a describable state, in mercury vapor at low pressures the atoms find enough room, even if measured in millionths of a millimeter, to express their individuality. (In the germicidal lamp, which has the lowest pressure of mercury vapor in commercial mercury lamps, the number of mercury atoms in a cubic centimeter is approximately half a million billion!) At pressures of a hundred or more atmospheres, in the ultra-high-pressure mercury-vapor lamps, the distinction between the two types of radiation tends to become blurred. (See Figure 16.)

The complication of the spectrum of low-pressure mercury vapor is to be attributed to the large number of alternative processes, each of which may be carried out, at any instant, by some of the atoms present. An atom which simultaneously radiates at two or more wavelengths is apparently as unusual as a vocalist who sings chords.

The mercury atom, according to present-day theory, comprises a small ($\approx 10^{-12}$ cm) but heavy nucleus—which may be regarded as composed of 80 positively-charged hydrogen ions (protons) and from 116 to 125 neutrons (uncharged particles of mass approximately the same as the proton)*—together

* This variation in the number of neutrons affects the atomic weight and the stability, as indicated by the relative abundance of the 7 "stable" isotopes and the radioactivity of the other 3, but has little effect on other physical and chemical properties. A variation in the number of electrons gives ions, negative if the number of electrons exceeds 80, positive if it is less than 80.

with 80 negatively-charged electrons, arranged in several concentric "shells" about the nucleus (*4*).

The individual electrons in an atomic arrangement, and likewise the atom state as a whole, are characterized by certain integral or half-integral numbers called quantum numbers. In the early days of spectroscopy these were represented by the ordinal numbers of the lines in a spectral series and designations for the various series of lines, now represented by the letters *s* (sharp), *p* (principal), *d* (diffuse), and *f* (fundamental), used to designate series of electronic and atomic *states*. In the Bohr-Rutherford atom model these numbers appeared as the parameters of the Bohr orbits. The Heisenberg "uncertainty principle" has made the orbits nebulous, and the quantum numbers now represent little more than the constants of integration of certain quantum-mechanical formulas. The experimental physicist still insists that a picture is possible, even if there are some difficulties in making it correspond to all the finer details.

According to the present-day quantum-mechanical interpretation of atomic structure, the changes in atomic arrangement associated with radiation are not continuous ones, but are limited to "permitted" transitions between distinct electronic arrangements, the difference in energy between the initial and the final state appearing as a "quantum" of radiation.

The different electronic arrangements—or maybe one had better say the resulting energy state of the atom—are shown diagrammatically in Figure 1. It is to be remembered that when a mercury atom is excited, one or more of the electrons move out to positions represented by states shown on the diagram. The disturbed electrons may move out to any of the states represented in Figure 1 (or to the other higher energy states not shown on the diagram), and when an electron or electrons return to the ground state or to some intermediate state shown on the diagram, a quantum of radiation is given off. One atom gives off radiation of one wavelength at a time. Thus many atoms take part in the production of the mercury spectrum.

When only one electron is in a quantum state higher than that it occupied in the ground state of the atom, the energy level and any possible downward transitions may be attributed to that electron. Excited states are known, however, in which as many as three electrons are in quantum states higher than those in the ground states in a radiation transition. In such cases it is hardly possible to assign the quantum state of the atom to a particular electron.

In the absence of a continual supply of energy to the electrons, the atoms will all "gravitate" to the arrangement of least energy, commonly called the "ground state" of the mercury atom. This is consequently, the normal state of the atoms of unexcited mercury vapor.

A complete specification of even this ground state is quite complicated,* as the following shows:

* In general, S will be the vector sum of the spins, *s*, of all the electrons not in closed shells; *s* is numerically ½ for each electron. L, similarly, is the vector sum of the *l*'s, and the azimuthal quantum number *J* will be the vector sum of *S* and *L*, the range of possible values of *J* extending from the difference $|L - S|$ to the sum, L + S.

($_{80}$Hg: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}\ 4f^{14}\ 5s^2\ 5p^6\ 5d^{10}\ 6s^2$). Arabic numerals represent total (or principal) quantum number n; s, p, d, f signify electrons with orbital quantum number respectively $l = 0, 1, 2,$ or 3, etc.; the exponents give the number of electrons with a particular n and l, e.g., $5d^{10}$ signifies a group of ten electrons with $n = 5$ and $l = 2$. Since the number of electrons permitted to have the same n and l is $4l + 2$, $5d^{10}$ represents a complete (or closed) shell of electrons. The resultant spin, S′, orbital quantum number, L′, and azimuthal quantum number J′ of a closed shell are all zero. Since the ground state of neutral mercury has *only* closed shells, its resultant quantum numbers S, L, J are all zero.

Since, however, most of the spectrum lines both of neutral and of singly ionized mercury involve states in which only one or both of the outermost (6s) electrons are disturbed, for most purposes only these two electrons need to be located. A further simplification (permissible for all the mercury lines to be discussed in this paper) is to use designations that are strictly correct only for the limiting case of Russell-Saunders coupling, that is to say, for atoms in which the resultant of the orbital angular momenta combines with the resultant of the electron spins to give the resultant angular momentum of the atom*.

Figure 1 gives a diagram of some of the energy levels (or states) of the mercury atom and the wavelengths of the radiation associated with the various transitions. These levels have been worked out empirically from the complicated mercury arc spectrum, but have been given designations based on quantum theory. Many different designations for the same state, e.g., $1p_3$, 1^3P_0, 2^3P_0, 6^3P_0, will be found in the earlier spectroscopic literature. States whose electrons have respectively the same quantum numbers, but different orientations, are said to belong to the same "configuration", e.g., (6s, 7p). Such states have been grouped in Figure 1.

The quantum states of any atom are classed as even or odd, and as singlet, doublet, or triplet, etc., states. "Even" states are those for which the arithmetic sum of the orbital quantum numbers, l, for all the electrons is an integral multiple of 2. Since all but two of the electrons (for the excited states of mercury here considered, in which one of the 6s electron remains in that shell while the other is "promoted"), are in complete shells, and $l = 0$ for this remaining 6*s* electron (as for all s-electrons) the resultant orbital quantum number, L, of the atom is identical with the orbital quantum number, l, of the single excited electron; in spectroscopic notation states with configurations (6s, n s)† are S-states (even); (6s, n p) are P-states (odd);‡ (6s n d) are D-states (even); (6s, n f)

* The mercury isotopes of odd atomic mass number exhibit a *hyper*fine structure of their energy levels due to interaction with the nuclear spin. For the even isotopes (with zero nuclear spin) the solitary energy levels differ slightly from isotope to isotope.

† In addition to 78 electrons in closed shells, one electron in the *6s* state and another in some other s-state.

‡ The customary methods of indicating odd states are the use of italics, and of superscript *o*; see Fig. 1.

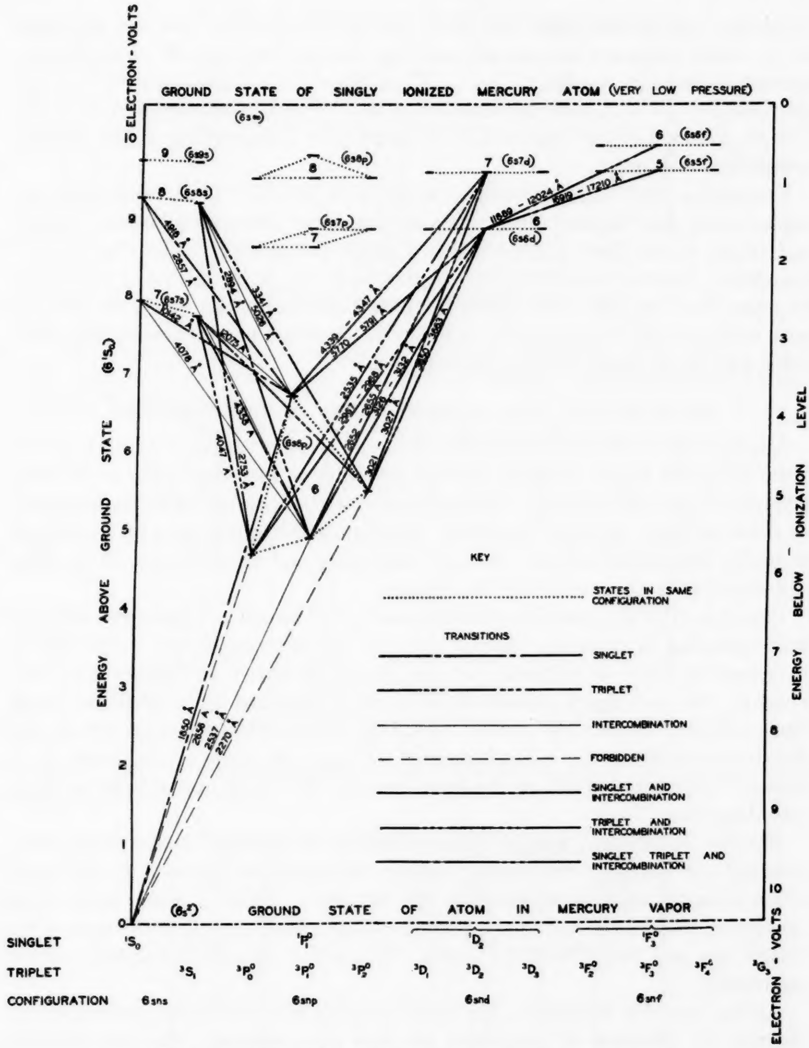

Fig. 1. Energy-level diagram for arc spectrum of mercury

are *F*-states (odd); (6s, n g) are G-states (even), etc. The states of the neutral mercury atom here considered are singlet or triplet states.*

* For ionized mercury, Hg^+, $S = \frac{1}{2}$, and all the atomic states are "doublets" with $J = L \pm \frac{1}{2}$. When $L = 0$ only one state, with $J = \frac{1}{2}$, results, but it is still called a "doublet S" state, a name perhaps justified by the fact that it becomes a doublet in a magnetic field (Zeeman effect).

"Singlet" states are states for which the electron spins of the two electrons not in closed shells are anti-parallel, so that the resultant spin S = 0, and the azimuthal quantum number J = L. When the electrons spins of two electrons are "parallel", S = 1, and the states are called "triplet" states since (except for L = 0), J may have the values L − 1, L and L + 1, depending on the relative orientation of S and L.

Transitions from singlet to singlet states give "singlet" lines, from triplet to triplet states give "triplet" lines; "intercombination" transitions between singlet and triplet states have a much lower *a priori* probability; while "forbidden" transitions, between states both of which have J = 0, or in which J or L changes by more than one unit, or in which the initial and final states are both even, or both odd, are still less probable—but may be observed under exceptional conditions, e.g., in strong electric or magnetic fields.

THE RADIATION FROM MERCURY VAPOR AT HIGH PRESSURES

Another type of departure from the ideal undisturbed radiation of the mercury atom is caused by the presence of high pressures of mercury vapor or of other ("foreign") gases or vapors. Three effects are to be observed, the disappearance of states of high principal quantum number n; the appearance of transitions normally forbidden, and the marked broadening and displacement of the lines associated with the remaining transitions.

One of us (B.T.B.) has measured the contours of broadened lines from mercury arcs operating at pressures ranging from 28 to 136 atmospheres. The results, expressed in terms of intensity per unit input are shown in Figures 2 to 5 inclusive. On each figure there is shown a curve obtained under identical conditions with an H-1 lamp as source. This curve shows the apparent broadening due to the width of the monochromator slits and the circle of confusion of the lenses. The actual width of the lines from an H-1 lamp probably is less than one Ångstrom.

For the 5770-5791Å group, the broadening of the lines seems nearly symmetrical; for the other lines whose contours are shown in Figures 3–5, the broadening is much more pronounced on the red side. There is also a shift of the maximum toward the red as the pressure is increased, except in the case of the 3650Å line and the 5770-5791Å group. These lines are shifted slightly toward the violet.

As the lines are broadened, the peak intensity per watt input decreases even though the efficiency of producing the line is increasing. The contradiction to this statement in the case of the 3650-3663Å group for the H-1 and H-3 lamps is only apparent and is due to the relatively large absorption of the arc tube of the H-1 lamp for radiation of these wavelengths. None of the data have been corrected for absorption by the arc tube and the outer jacket.

The 3650Å line furnishes an exception to the rule that close groups of lines are completely merged at both 106 and 180 atmospheres. The 4078Å line is still in evidence at 136 atmospheres, but the peak due to the 4344 and 4348Å lines is not.

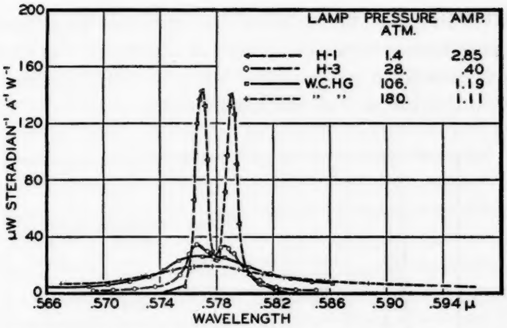

FIG. 2. Spectral intensity per watt input for the 5770–5791Å group from an H-1, an H-3 lamp, and for a water-cooled lamp at 80 atmospheres (equivalent to an H-6 lamp) and at 136 atmospheres.

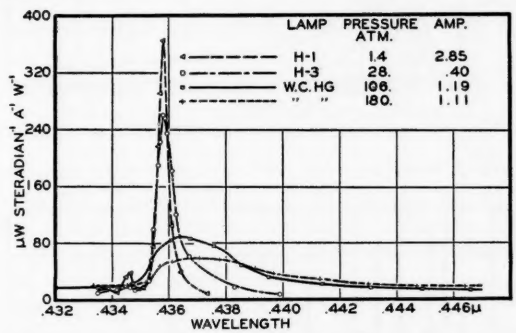

FIG. 3. Spectral intensity per watt input for the 4358Å line from various mercury lamps. (See Fig. 2.)

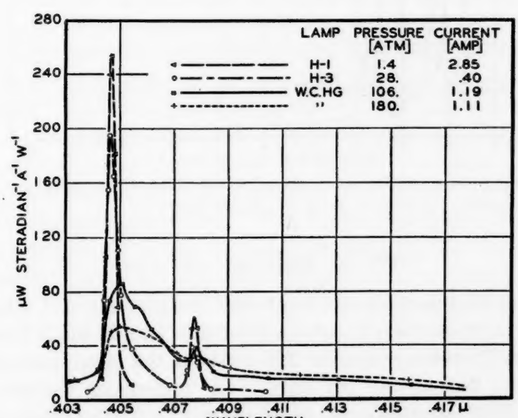

FIG. 4. Spectral intensity per watt input for the 4047 and 4078Å lines from various mercury lamps. (See Fig. 2.)

At 106 and at 180 atmospheres, all of the lines are superposed on a strong background of continuous radiation. This is shown by Figure 6, which gives the complete spectrum for a water-cooled lamp at 140 atmospheres. The peak at about 4800Å on this graph is of unknown origin.

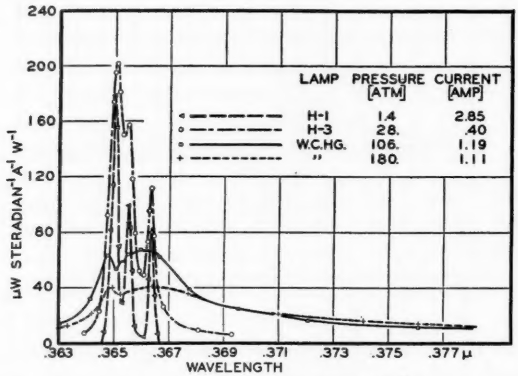

Fig. 5. Spectral intensity per watt input for the 3650–3663Å group from various mercury lamps. (See Fig. 2.)

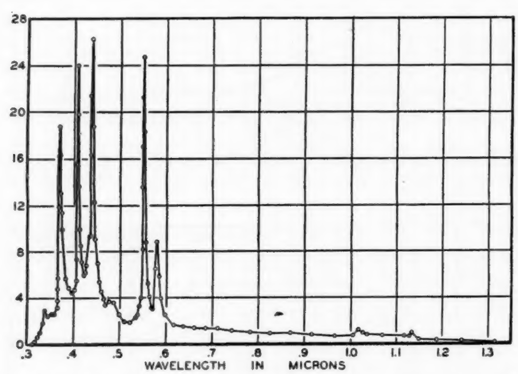

Fig. 6. Spectral intensities for a water-cooled capillary lamp operated at a pressure of about 140 atmospheres. (See J. O. S. A. *27*, 85–86 (1937).)

TYPES OF MERCURY ARC LAMPS

The first successful mercury arc lamp was brought out by Cooper Hewitt (*5*) in 1902. This lamp consists of a tube 125 cm in length and 2.5 cm in diameter and operates on 72 volts, consumes 266 watts in the lamp, and gives light at a lamp efficiency of 24.5 lumens per watt. The pressure of the mercury vapor in this lamp is 0.0003 atmospheres, which puts this in the class of low-pressure mercury-vapor lamps. It requires special apparatus (Figure 10) to start and

operate this lamp. The lamp contains an excess of mercury, in fact, the cathode consists of a pool of mercury. For direct current operation, the mercury pool serves as the cathode and the anode is, of course, at the other end of the tube. For alternating current operation, there are two anodes at the end of the tube opposite the mercury pool, which anodes carry the current in turn as the voltage alternates, the mercury pool always serving as the cathode. The lamp acts as a rectifier and the current is thus a pulsating direct current.

Following this lamp, mercury arc lamps in quartz tubes were developed. These lamps were for either direct or alternating current operation. They operate at a much higher pressure of mercury vapor—about one atmosphere—and are used as sources of ultraviolet radiation for special types of sterilization and were formerly used as sun lamps.

The mercury arc lamp that operates at the lowest mercury-vapor pressure is made and used for two purposes. This is the mercury arc used for the germicidal lamp and as the source of the exciting radiation for the fluorescent lamps. This arc operates with a mercury-vapor pressure of several microns. At this pressure and for the method of exciting this arc, many of the mercury lines are radiated. However, a large percentage of the electrical energy input to the positive column is radiated by the line at 2537Å which has lethal effect on certain germs and bacteria (*6*).

For the germicidal lamp a glass is used that transmits a large percentage of this radiation because the radiation is to be used outside of the tube. The fluorescent lamp is in a glass tube that transmits practically none of this radiation since here the radiation is used inside the tube, and also, this radiation is quite harmful to the eyes so must not be allowed to escape in a room used for general purposes.

Several years ago there was developed in Europe a new mercury arc lamp (*7*). This lamp is constructed to consume 400 watts and to operate with the mercury vapor at a pressure of 1.2 atmospheres. To control the mercury pressure and thus insure more uniform operating conditions, a definite amount of mercury is put into the lamp and the lamp operated so that the bulb wall is at such a temperature that all the mercury is vaporized and held at a pressure of about 1.2 atmospheres. To aid in maintaining the mercury vapor at the proper temperature, a double walled bulb is sometimes used. These lamps have oxide coated electrodes and contain, besides the mercury, a small pressure of inert gas. For starting the arc, a third electrode is provided which is located near the electrode at the base of the lamp. Two lamps of this type are now made, the 400-watt lamp designated as the H-1 mercury lamp, which has a double walled bulb, and a smaller lamp, the 250-watt, of the same type, designated as the H-2 mercury lamp. The smaller lamp operates at a pressure of about 0.6 atmosphere and has a single wall bulb. The 400-watt lamp gives about 16,000 lumens which is about 40 lumens per watt, while the 250-watt lamp gives 7,500 lumens which is about 30 lumens per watt.

The study of the radiation from mercury arcs with increasing mercury-vapor pressure was continued and resulted in the development of mercury lamps of

still smaller size and higher wattage which operated at a very high mercury-vapor pressure (*8*). Following the H-1 and H-2, the H-3, H-4, H-5, and H-6 lamps were developed. The H-3 lamp consists of a quartz tube 4 mm in internal diameter and with an arc length of 18 mm. It operates on an arc voltage of 250 and consumes 85 watts which results in the mercury pressure of 26.5 atmospheres and gives light at 35 lumens per watt. The H-4 lamp is in a quartz tube 7 mm in internal diameter with an arc length of 24 mm. It operates at an arc voltage of 130 and consumes 100 watts which results in a mercury pressure of 8 atmospheres. This lamp is also used as the basis of a new S-4 sun lamp. Construction data on the other H-lamps are given in Table 3.

As this work was pushed to a higher and higher vapor pressure, the input and the resulting temperature of the bulb became so high that even for a quartz bulb, forced cooling was necessary either by compressed air or by flowing water. A 1000-watt, high-pressure, water-cooled mercury arc lamp (*9*), the H-6, was developed. This lamp is in a quartz tube 2 mm in internal diameter, 6 mm in outside diameter, and with an arc length of 25 mm. It gives light at 65 lumens per lamp watt. Many special lamps of this type have been made for experimental purposes and some of their characteristics studied as shown in the following curves and tables.

Professor C. Bol, who started the work on these very high-pressure arcs at the Philips Company lamp factories in Holland, and who has been located at Stanford University for the past ten years, has continued the study of these high-pressure mercury arcs. Some mercury arcs that he has developed operate at a very high pressure. Figure 17 shows the spectrum of one of his arcs that is in a quartz tube with a 1 mm bore and an arc length of 10 mm that was operated at different pressures up to about 1000 atmospheres. This arc tube, which was mounted in a special container with windows for observational purposes, was surrounded by water at a pressure of 700 atmospheres. The water at this pressure served two purposes: first, keeping the arc tube cool, and second, keeping it from bursting at this very high pressure of operation.

Two special types of sun lamps were developed about twelve years ago, the S-1 and the S-2, which are tungsten mercury arcs, and the G-1 and the G-5 sun lamps (*10*) which are at times spoken of as mercury glow lamps.

Several new types of quartz mercury arcs (uviarcs) have been introduced; also, a 1200-watt mercury arc in a tube of special glass 3 cm. in diameter with an arc length of 125 cm for photochemical use. A 3000-watt arc in a tube 120 cm long and about 1.2 cm in diameter has also been developed for lighting purposes.

STARTING AND OPERATING MERCURY ARCS

Since mercury-vapor arcs will not start on the low voltage necessary to operate them, several special methods are used for this purpose which will be explained by showing how certain arcs are started. The methods described are in some cases simply different applications of the principles that are used to start other mercury arcs. These methods are based upon (a) breaking a cir-

cuit in the arc tube itself so that the resulting arc and ionization will start the main arc; (b) breaking a circuit through an inductance so as to make use of the induced voltage to start the arc. Mercury arcs may also be operated in series from a constant current transformer. In such an arrangement the voltage is high enough to start the arcs in turn. Some provision must be made for shorting any lamp that fails. Another method, and one used in several types of arc, is to operate the arc from a transformer that has a large open circuit voltage, and due to the drooping characteristics of the transformer, the operating voltage depends upon the current that is drawn. Thus when the arc starts and draws a large current, the voltage given by the transformer drops to that necessary to operate the arc. Oxide coated cathodes may be used for the mercury arc. Sometimes a third electrode is used and placed near one of the other electrodes so as to shorten the arc gap. It has also been found possible to start and operate mercury arc lamps with tungsten electrodes which are not

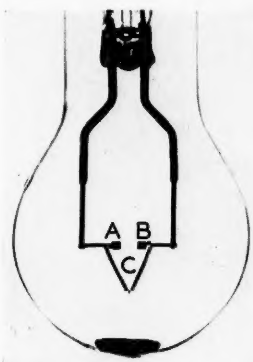

FIG. 7. General arrangement of electrodes and filament in type S-1 sun lamp

activated. A third tungsten electrode, likewise unactivated, may be used to aid in starting the lamp. In many arcs, a few millimeters pressure of one of the inert gases is put in with the mercury. Due to the low sparking potential of the gas used, an arc can be started through it with a much lower voltage than that required to start an arc through the vapor of mercury at room temperature. The arc through the gas heats the mercury in the tube and raises its pressure so that it will carry the current. To be sure, the ionization due to the arc already flowing is a factor in starting the arc through the mercury vapor.

The method used to start the arc in the S-1 and S-2 and the G-1 and G-5 sun lamps is as follows: The S-1 lamp is operated from a transformer that gives about 35 volts on open circuit. When the lamp is first turned on, the filament "C", Figure 7, is heated to a high temperature and as soon as it is hot enough (i.e., in a few seconds) to give off sufficient electrons, an arc is started across the ends of the filament. At first the electrodes "A," and "B" are alternately the anode, and the opposite end of the hot filament alternately the cathode. Soon

these electrodes are heated by bombardment to such a temperature that they will give the necessary electrons to maintain the arc, and then the arc passes to these electrodes. As soon as the arc starts, the voltage supplied by the transformer drops off as shown by Figure 8. Thus the arc is maintained at very nearly a constant value of both current and voltage. The S-2 sun lamp is started in a similar manner. The G-lamps have unipotential oxide-coated electrodes which are heated by a coil mounted inside of each electrode. When the current is first turned on, it passes through these two heater coils in series,

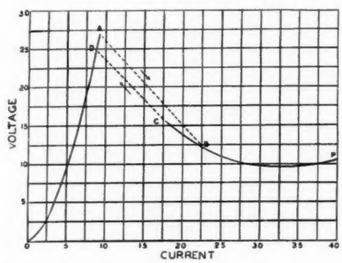

FIG. 8. Voltage-ampere curve for type S-1 sun-lamp transformer

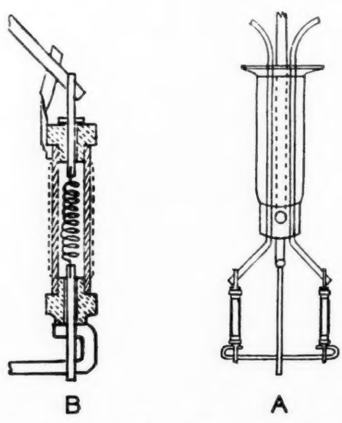

FIG. 9. The indirectly heated electrode (B) and the assembled mount for the G-1 lamp (A)

Figure 9. As soon as the electrodes are heated to a temperature such that they will give sufficient electrons, an arc is started between them. The voltage drop across the lamp is then reduced to a much lower value. When the lamp is operated, a part of the current passes through the filament and a part through the arc since the oxide coated cathodes are directly connected to the input leads, thus in part shorting out the heater filaments. These lamps require a special type of ballast or transformer for operation. The heaters for the S-1 and S-2 and the G-1 and G-5 lamps are tungsten filaments which are left in the circuit

all the time and operate at a reduced voltage, i.e., lower temperature. The fact that the operating voltage of the arc is less than the starting voltage is the cause of the lower wattage and lower temperature of the heater filament of the S-1 and S-2 sun lamps, and the lower operating currents for the G-lamps allows these heater filaments to operate at a lower temperature.

The mercury arcs that are started by breaking a circuit inside the tube employ a pool of mercury at one end and sometimes at both ends of the tube. To start these arcs, the arc tube is tipped so that a thread of mercury flows from the mercury pool to the electrode at the other end and makes electric contact, and thus carries a current that is limited by the characteristics of the circuit. As this thread is broken when the tube is returned to its normal position, an arc is started. This produces sufficient ionization to maintain the arc as the gap is lengthened by the mercury flowing into the lower end of the tube. A resistance or a choke coil of the proper value to control the current is included in the lamp circuit. This is the method that was formerly used to start the Cooper Hewitt lamp and is the one now employed to start the older types of the quartz mercury arcs, such as the uviarcs.

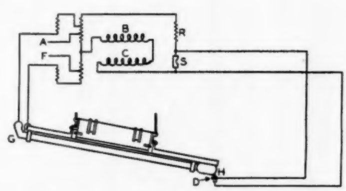

FIG. 10. Wiring diagram of a.c. auxiliary for Cooper Hewitt mercury arc

The electrical connections for the method now used to start the Cooper Hewitt lamp (*5*) is shown in Figure 10. When the lamp is first turned on, current passes from "A" through "R", the shifter switch "S", the inductance coils "B" and "C", and back to the line at "F". After a few seconds, the shifter switch "S", electromagnetically operated, opens the circuit and thus the induced voltage kick, due to the stopping of the current through the inductance "B" and "C", throws a high voltage across the lamp "G-H" and across the cathode "H" and the starter band "D". This starter band consists of a piece of metal on the outside of the bulb containing the mercury. When the high voltage due to the inductive kick—of the order of 3000 volts for the Cooper Hewitt lamp starter device—is thrown across this starter band and the mercury pool, a current passes between the surface of the mercury pool and the starter band. The ionization due to this current is enough to cause an arc to strike between the main electrodes of the lamp. The resistance "R" in the circuit of the starter band prevents the circuit from the starter band to the mercury pool from being directly a short circuit on the main arc. After the arc is started, it is maintained by the voltage supplied by the transformer and is kept from drawing too much current by the characteristics of the circuit.

Another method of starting the mercury arc is to use three electrodes, which

may be oxide coated, with two of them near each other, and a transformer that has a high enough voltage on open circuit to start an arc between the two neighboring electrodes. As soon as this happens, enough ionization results to allow an arc to strike between the two main electrodes of the lamp. A high resistance in series with the third electrode prevents it from short circuiting the main arc. This is the method used to start the H-1 and the H-2 mercury lamps.

The very low-pressure mercury arc used as the germicidal lamp and as the source of the exciting radiation for the fluorescent lamp is started as follows: first, a few millimeters of an inert gas are put into the tube with the small amount of mercury, and the lamp is equipped with oxide coated cathodes that are so connected, Figure 11, that they are preheated by the first current that flows in the lamp. When the current is first turned on, it passes through the choke "K", Figure 11, the two oxide coated electrodes "B" and "C," the switch "S", and back to the line. After the current has been flowing for a very short time,

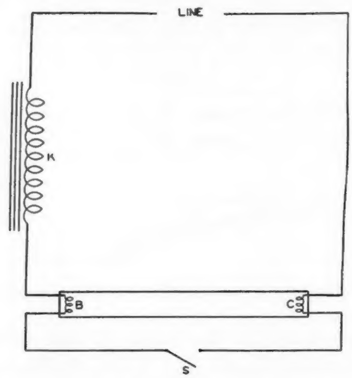

FIG. 11. Starting and operating wiring diagram for low-pressure mercury arcs (the germicidal lamp and the arc used as the exciting radiation for fluorescent lamps).

which is selected as that necessary to preheat the oxide-coated cathodes to such a temperature that they will give enough electrons to start the arc, the switch "S" opens, the current through the choke "K" is broken, and the voltage due to the resulting inductive kick is enough with the help of the preheated cathodes to start the current through the low-pressure gas present. This flow of current through the gas heats the mercury in the tube and thus raises the pressure of the mercury vapor so that it then carries most of the current.

At least three different types of delayed-action switches have been used to open the circuit for starting these lamps: (1) an electromagnetic switch operated by the choke "K"; (2) a thermal switch consisting of a bimetallic strip heated by a small coil of wire near it, which, when the bimetallic switch is heated, bends in such a manner as to open the circuit; (3) a glow switch (*11*), Figure 12, made of a small tube containing at low pressure one of the inert gases, and provided with electrodes of such size, separation, and material that an arc will start on

the voltage applied from the regular supply mains. When the arc is started, it heats up a bi-metallic switch "A" which closes the circuit and allows a larger current to pass through the electrodes of the lamp. As soon as the switch is closed, the arc stops and the bimetallic strip "A" cools off and opens the circuit. The parts of each type of switch are selected as to size and material to give the necessary time delay. The very high-pressure mercury arcs are started by the use of a reactive transformer that gives a high voltage on open circuit. These lamps contain one of the inert gases at low pressure to aid in starting the arc.

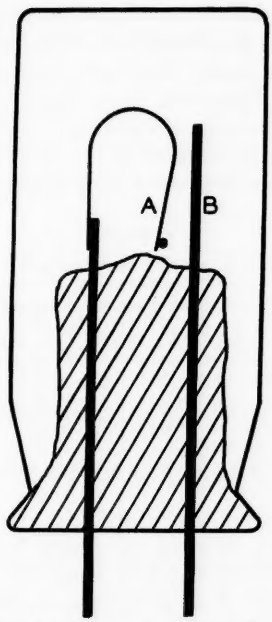

FIG. 12. Glow switch for use in starting fluorescent lamps

CHARACTERISTIC RADIATION OF THE MERCURY-VAPOR ARCS

The distribution of the energy radiated by a mercury arc, among the different wavelengths, is one of its important characteristics. As has already been pointed out, this depends upon the pressure of the mercury vapor in the tube. Mercury at a very low pressure—a few microns—may be excited to radiate by resonance, that is, by allowing the radiation of wavelength 2537Å to fall upon it, which excites the mercury vapor to give out this same radiation—called the resonance radiation of mercury vapor. By this excitation, practically all of the output consists of resonance radiation.

A low-pressure mercury arc, the germicidal lamp, which operates with a pressure of several microns, somewhat higher than the pressure for the most efficient production of radiation by resonance reemission, nevertheless radiates

a very large percentage of the input energy in the line at 2537Å. This radiation is produced more efficiently in the positive column than in the "negative glow" at the cathode or in the anode glow. To attain high efficiency, the greater part of the voltage must be spent in the positive column. Thus the lamps based on this radiation—the fluorescent lamps—are necessarily long in relation to their diameters. As shown in Table 1, better than 60 per cent (about 70 per cent for the best conditions) of the input electrical energy into the positive column of these low-pressure mercury arcs in a tube 1 inch in diameter and 18 inches in length, at an outside temperature of 40°C, is radiated by this line. Since the positive column consumes about 70 per cent of the energy input into these tubes, these figures show that more than 50 per cent of the input energy may be radiated in this narrow wavelength band. The low-pressure mercury arc used as the exciting radiation for the fluorescent lamp radiates about 50 per cent of the electrical energy input in this narrow wavelength region. When one remembers that the tungsten filament as operated in the 40-watt, 115-volt, 1000 hour life lamp (T = 2720°K) radiates only about 7.5 per cent of the input energy within

TABLE 1

Efficiency of production of mercury line radiation

CURRENT (AMP.)	BULB WALL TEMP.	PER CENT* CONVERTED INTO EACH LINE							SUM	PROPORTION IN 2537Å LINE	LUMENS PER WATT*
		λ2537	3129	3654	4047	4358	5461	5780Å			
0.25	48°C	62	0.53	0.45	0.59	1.30	0.86	0.18	65.9	94%	5.5
0.50	57	55	0.68	0.62	0.86	1.45	1.26	0.27	60.1	92	7.3
1.00	69	40	0.89	0.82	1.02	1.79	1.49	0.39	46.4	86	10.0

* Of positive column input, for a low pressure discharge tube 1 inch diameter in still air at 25°C.

the visible spectrum which covers a wavelength band of about 2700Å (3900–7600) and that this is only increased to about 13.5 per cent for the 120-volt, 1500-watt, 1000 hour life (T = 3020°K) tungsten filament lamp, it can be seen what a high percentage of the input energy is radiated in this narrow wavelength band.

Maximum efficiency of production of resonance radiation in a low-pressure mercury arc is attained only when the coolest portion of the tube wall has a certain temperature (*12*). This is to be expected because the pressure of the mercury vapor in the tube depends on the temperature of the walls. If this pressure were too low, the concentration of mercury atoms relative to the inert gas atoms would be insufficient for maximum efficiency; if it were too high, i.e., the wall temperature too high, most of the resonance radiation would be absorbed before it reached the tube wall and much of it would be lost. The spectral distribution of the radiation from mercury vapor varies with the pressure, a smaller proportion being resonance radiation as the pressure is increased. The curves in Figures 13, 14, and 15 show how the production of the resonance radiation depends (1) upon the length of the tube (for a given diameter), (2)

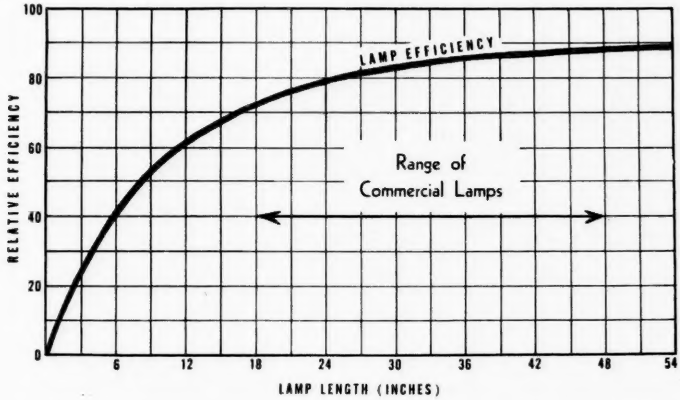

FIG. 13. Relative efficiency of production of radiation in wavelength 2537Å and length of tube (1 inch in diameter).

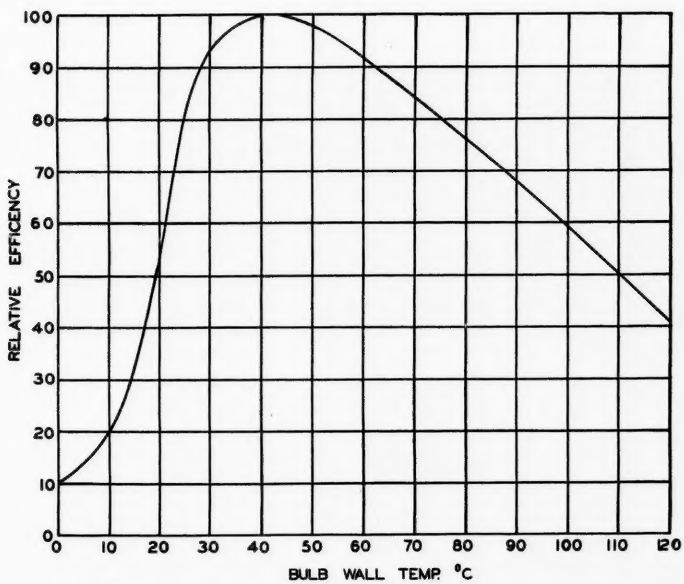

FIG. 14. Percentage of total input energy converted into mercury resonance radiation (wavelength 2537Å) for different temperatures of tube wall for a discharge tube 1 inch in diameter.

upon the temperature of the walls of the tube, and (3) upon the current density for a definite tube diameter.

Figures 16 and 17 show how the spectrum of the mercury arc varies with the

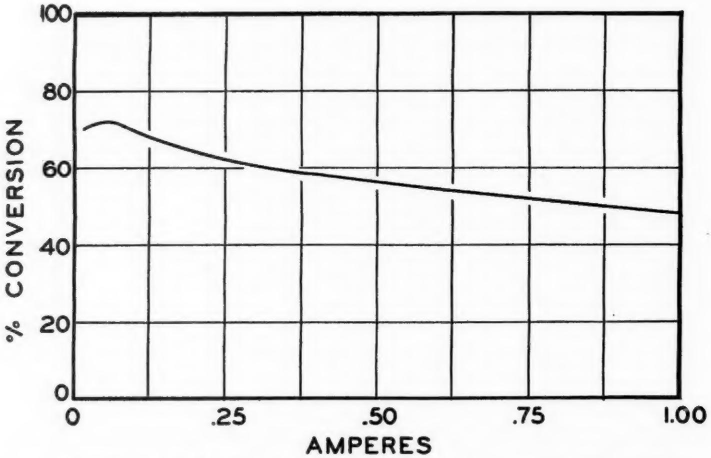

FIG. 15. Percent of total input energy converted into mercury resonance radiation (wavelength 2537Å) for different currents for a discharge tube 1 inch in diameter held at 40°C.

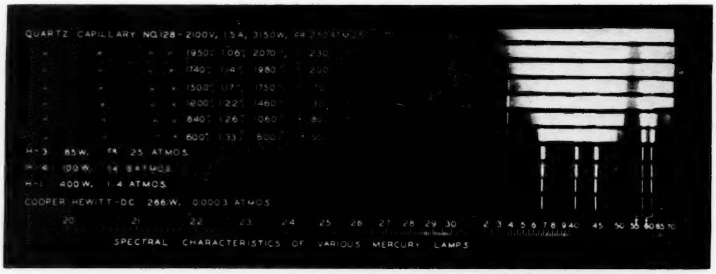

FIG. 16. Spectrum of a number of mercury vapor lamps at different operating pressure

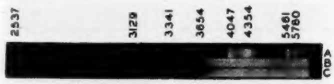

FIG. 17. Spectrogram by C. Bol at Stanford University: quartz mercury arc with gap of 10 mm. and bore of 1 mm. operating in steel container with the circulating water under a pressure of 700 atmospheres

	Volts	*Amps.*	*Watts*
A	1160	1.15	750
B	1860	1.5	1375
C	2300	2.6	1580

The pressure of the mercury vapor probably ranges from 500 to 1000 atmospheres.

pressure of the mercury vapor. This spectrum at very low pressure of the vapor consists of very narrow lines which increase in width as the temperature, i.e.,

the pressure, rises until at a very high pressure, such as that reached in the experiments of Professor Bol, there is no evidence of line radiation; that is, the spectrum of a mercury vapor has become continuous.

The increase in continuous radiation from the mercury arc with increased pressure (*13*) is shown in Figure 18. This shows the spectral energy distribution for the water-cooled mercury arc in a quartz tube with a bore of about 2 mm. and an arc length of about 25 mm. for four different conditions of operation—that is for four different pressures of the mercury vapor. Curve A is for the arc

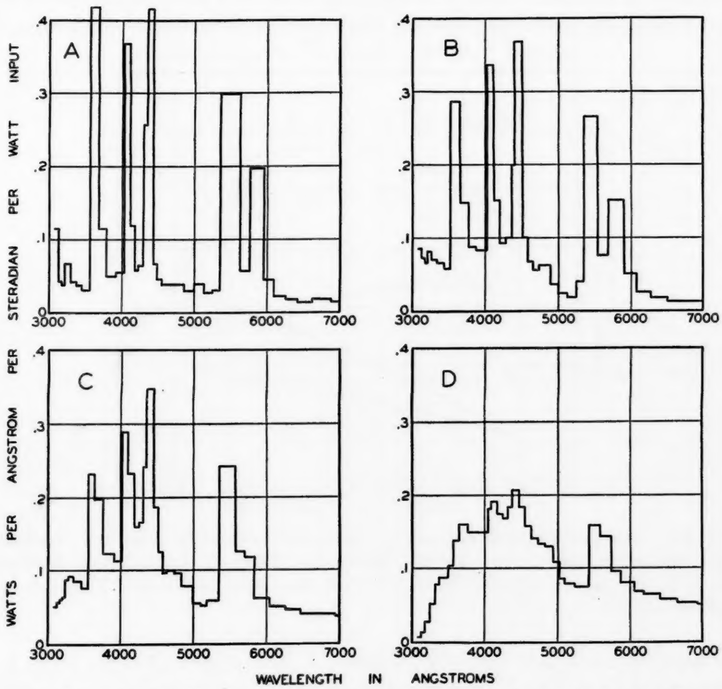

FIG. 18. Spectral distribution of energy for a mercury arc in a tube 2 x 6 x 25 mm. for various pressures. Curve A, for mercury vapor pressure of 54 atmospheres; Curve B, for mercury vapor pressure of 102 atmospheres; Curve C, for mercury vapor pressure of 197 atmospheres; Curve D, for mercury vapor pressure of 319 atmospheres.

operated at a pressure of 54 atmospheres, which is lower than the normal operating pressure for this lamp (the H-6); Curve B is about the normal operating pressure for this type of mercury lamp; and Curve C and Curve D are for higher pressures. There is considerable continuous radiation given by a mercury vapor arc at 54 atmospheres pressure, and this continuous radiation increases markedly with increased pressure, as is shown in Curves B, C, and D.

While the changes in the spectrum due to a change of the vapor pressure of the mercury vapor are readily apparent in Figure 18, the amount of this change

in five arbitrarily chosen regions of the spectrum is shown more definitely in Figure 19 where the radiation in these regions is plotted against the pressure of the mercury vapor.

Region I extends from 3000 to 3800Å and contains the 3654Å line. Region II, extending from 3800 to 4600Å is dominated by the 4047 and the 4358Å lines. The next region, Region III, from 4600 to 5400Å has no prominent lines and can be considered as one where background radiation predominates. The fourth region from 5400 to 6000Å embraces the 5461Å green and the 5780Å yellow lines of mercury, the two lines which, because of their strength and favorable wavelength, contribute most of the luminous efficiency of the lamp. The

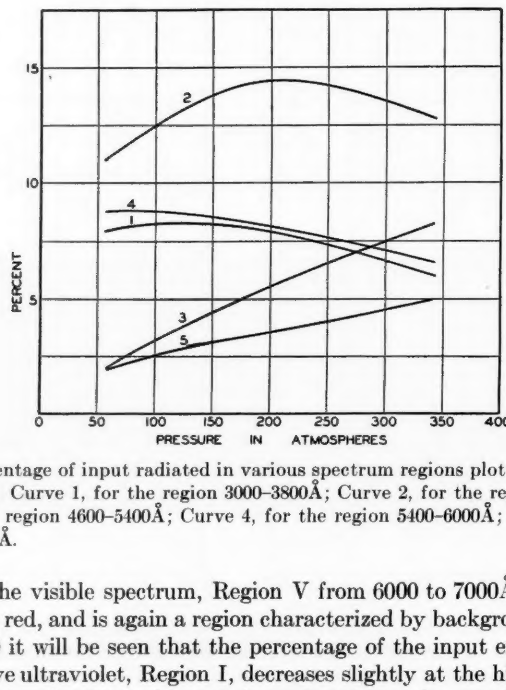

FIG. 19. Percentage of input radiated in various spectrum regions plotted as a function of the pressure. Curve 1, for the region 3000–3800Å; Curve 2, for the region 3800–4600Å; Curve 3, for the region 4600–5400Å; Curve 4, for the region 5400–6000Å; Curve 5, for the region 6000–7000Å.

remainder of the visible spectrum, Region V from 6000 to 7000Å, takes in the orange and the red, and is again a region characterized by background radiation.

In Figure 19 it will be seen that the percentage of the input energy radiated in the long-wave ultraviolet, Region I, decreases slightly at the higher pressures for this lamp. Region IV is the most important from the standpoint of luminous efficiency, and the percentage of the input energy in it decreases slightly at the higher pressures. The green and the red continuous portions of the spectrum (Region III and V) respectively quadruple and triple the percentage of input energy radiated in these regions as the pressure is varied over the range shown, the amount of energy in either of these bands being almost directly proportional to the pressure.

The spectral distribution may be given either as a percentage of the total input or it may be given as the amount of energy that falls upon a unit area at a

definite distance from the lamp in a unit time for any selected wavelength interval. The percentages of the overall input radiated in selected spectral bands by some of the mercury arcs described above are given in Table 2. These percentages for any one arc do not add up to 100 because of end losses and because—for these lamps—a large percentage of the input is lost by the bulb either by convection or conduction or by low-temperature radiation. The intensity of the radiation for some low-pressure vapor arc tubes of the Cooper

TABLE 2

Per cent of over-all input radiated in different spectral bands by various mercury-vapor lamps manufactured by the General Electric Company

TYPE OF LAMP	BULB GLASS*	OVER-ALL INPUT WATTS	WAVELENGTHS (λ) IN ANGSTROMS								ULTRA-VIOLET (Wavelengths (λ) in Angstroms)	VISI-BLE	INFRA-RED
			Less than 2800	2800 to 3165	3165 to 3800	3800 to 5000	5000 to 6000	6000 to 7600	7600 to 14,000	14,000 to 26,000	Less than 3800	3800 to 7600	7600 to 26,000
H-1	772	456	0.00	0.00	0.94	3.2	5.6	0.56	4.8	5.9	0.94	9.4	10.7
H-2	172	294	0.00	0.00	0.95	2.8	4.2	0.24	2.8	3.1	0.95	7.2	5.9
H-3	772	105	0.00	0.08	2.9	4.8	5.1	0.94	4.4	7.0	3.0	10.8	11.4
AH-4	772	120	0.00	0.03	2.5	4.6	5.3	0.83	5.1	9.1	2.5	10.7	14.2
AH-5	774	284	0.00	0.14	3.1	4.7	6.7	1.16	6.5	7.1	3.2	12.6	13.6
AH-6	774	1170	0.00	0.43	5.4	12.6	8.9	3.0	6.0	0.00	5.8	24.5	6.0
AH-9	172	3350			0.66	3.6	6.5				0.66	10.1	
Cooper Hewitt	Lead	350	0	0.20	0.89	4.4	3.1	0.02	1.0		1.09	7.5	1.0
1200-watt†	973	1380		0.1	0.64	1.71	1.62				0.7	3.3	
360-watt‡	Quartz	417	4.5	4.3	3.7	3.2	4.1	0.28	2.3	1.9	12.5	7.6	4.2
15-watt Germicidal	972	17.5	13.2	0.22	0.19	1.62	0.67	0.01	0.01	0.00	8.8	2.3	0.01
S-1§	776	438	0.00	0.38	0.58	0.93	1.63	3.3	19.7	19.4	0.96	5.86	39.1
S-2§	776	145	0.00	0.21	0.32	0.57	0.92	1.70	10.3	11.2	0.53	3.2	21.5
S-4	721	118	0.005	2.1	3.7	4.3	5.2	0.80	5.0	9.0	5.8	10.3	14.0
G-1	776	46	0.00	0.31	0.35	1.18	0.89	0.00	0.30	0.00	0.66	2.1	0.30
G-5	982	113	0.00	0.35	0.37	1.33	0.91	0.00	0.35	0.00	0.72	2.2	0.35

* Number listed in this column designates type of Corning glass used for bulb or outer jacket.

† T9-½ Photochemical lamp.

‡ T6 Uviarc.

§ With axis 30° from vertical.

Hewitt type, together with some of their construction and electrical characteristics, as well as like data for two uviarcs, are given in Table 2. As mentioned in the discussion of methods of starting, uviarcs have been developed using unactivated tungsten cathodes. These lamps contain a measured amount of mercury (a few milligrams) and a small amount of argon gas to help start the arcs. The amount of mercury in the lamp is so selected that when the lamp operates normally, it contains no liquid mercury. The watts per unit length of

the tube are experimentally selected to give the best operating conditions at maximum radiation output and efficiency. These lamps are operated from properly designed reactor transformers.

TABLE 3

Dimensions, operating characteristics, light output and spectral intensities perpendicular to axis of arc for various mercury-vapor sources of visible and of long-wavelength ultraviolet radiation

LAMP	COOPER HEWITT	H-1	H-2	H-3	AH-4	AH-5	AH-6	AH-9	1200-WATT T9-4 PHOTO-CHEMICAL
Bulb glass*		772	172	772	772	774	774	172	973
Inside tube diam. (cm.)	2.4	3.5	2.7	0.4	0.75	1.3	0.2	1.8	3.0
Arc length (cm.)	128	15.5	10.5	1.8	2.4	4.3	2.5	122	124
Vapor pressure (atm.)	0.0003	1.2	0.6	27	9	6	106	0.4	
Lamp volts	72	140	70	230	140	135	880	550	128
Lamp amperes	3.7	3.1	3.9	0.43	0.82	2.08	1.42	6.1	10.4
Lamp watts	270	400	250	83	98	248	1060	3000	1,200
Overall watts	350	456	294	105	120	284	1170	3350	1,380
Lumens	6500	15,000	7200	3200	3800	11,500	64,000	130,000	13,500
Lumens per watt	24	38	29	39	39	46	60	43	11.2
Candles per mm.²	0.031	1.4	1.0	18	8		300		

WAVELENGTH BAND	PRINCIPAL LINES	SPECTRAL INTENSITIES (MILLIWATTS PER STERADIAN)								
2,950–3,000	2,967	0.0	0.0	0.0	0.02		1.2	33		6.0
3,000–3,050	3,022	0.5	0.0	0.1	0.23	0.06	4.3	66	0.0	
3,050–3,200	3,129	67	0.13	1.7	9.2	3.7	43	560	0.0	105
3,200–3,600	3,341	23	18.1	9.3	42	21	119	1920		25
3,600–4,000	3,650–3,663	290	420	270	280	290	800	5600	2,200	830
4,000–4,200	4,047	650	440	270	157	162	420	3600	3,800	900
4,200–4,600	4,358	830	910	510	270	330	790	6800	8,000	1,390
4,600–5,300		17	90	20	59	43	124	3100		
5,300–5,600	5,461	790	1240	600	300	330	900	4900	10,000	1,540
5,600–6,000	5,770–5,791	260	1210	600	195	270	910	4300	11,000	630
6,000–7,600		7	250	70	96	97	320	3450		
7,600–10,000			460	130	125	135	440	3400		
10,000–10,500	10,140	340	590	250	84	132	400	1070		
10,500–11,500	11,289		320	110	67	100	300	1250		
11,500–13,000	11,900–12,100		390	150	93	112	330	830		
13,000–14,500	13,570–13,955		480	200	107	156	440	250		
14,500–16,000	15,290		350	120	91	125	320			
16,000–20,000	16,900–17,100		960	340	260	380	820			
20,000–25,000			1040	330	320	430	700			

* Type of Corning glass used for bulb or outer jacket.

USES OF VARIOUS TYPES OF MERCURY VAPOR LAMPS

The many types of mercury lamps find various applications for general and special lighting purposes. The 125 cm. Cooper Hewitt mercury arc is still in use for general lighting purposes. The H-1 is employed widely for vari-

ous types of outdoor lighting as well as indoor lighting of factory spaces. The H-2, H-3, H-4, H-5 are used where a smaller lamp of this type is needed. The H-4 has two other uses: at times it is mounted in a red-purple bulb and used as a source of long ultraviolet radiation (i.e., 3650Å), for exciting certain materials, such as rugs in the aisles of theatres, to fluoresce. This lamp is also mounted in a reflector bulb (that is a PAR-4) and used with a purple corex screen for the projection of this long wavelength ultraviolet radiation. This lamp is also mounted in an ultraviolet transmitting glass and used as the S-4 sun lamp (see data under Sun Lamps). This lamp is also mounted at times in a reflector bulb made of an ultraviolet transmitting glass and used as a projector sun lamp. The H-5 may be mounted in ultraviolet transmitting glass and used as a source of ultraviolet radiation for various purposes. This lamp gives about 2.5 times as much ultraviolet radiation as the H-4. The H-6 lamp is used as a projector lamp, for photo-engraving, and other purposes. Some construction, electrical and radiation data on the H-lamps are given in Table 3. A new mercury arc, in a tube about 1.2 inches in diameter and 54 inches in length, consuming 3000

TABLE 4

Percentage of total light from mercury arcs operating at various pressures, from sun, from a tungsten lamp, of wavelength 6000–7600Å

SOURCE	MERCURY PRESSURE IN ATMOSPHERES	PER CENT OF LIGHT 6000-7600Å
Cooper Hewitt	0.0003	0
H-1 Lamp	1.4	1.0
H-4 Lamp	8	1.7
H-3 Lamp	29	1.9
Water-cooled capillary arc	110	7.0
Sun		20.0
500-watt, 115-volt tungsten		27.0

watts has just been offered. Data on the various mercury lamps as light sources are also given in Table 3.

COLOR OF LIGHT GIVEN BY MERCURY ARCS

The light given by the Cooper Hewitt mercury vapor arc is of the familiar bluish-green color. The change in the spectrum of the energy radiated affects the color of the emitted light. The increase of the continuous radiation in the blue-green region (Curve 3, Figure 19) and in the orange-red region (Curve 5, Figure 19) adds radiant energy where the usual low pressure arc is notably weak. The light given by these new high-pressure mercury arcs contains an appreciable amount of red (6000–7600Å) as shown by the data in Table 4 where data on some other sources are given for comparison. Colored objects illuminated by light from these high-pressure mercury arcs are not greatly distorted from their appearance in the daylight.

The color of the various light sources can be classified by use of the system of color specifications adopted in 1931 by the International Commission on

Illumination (*14*). In this system color is defined by the proportion of three standard colors called primaries in a mixture which matches in color the light investigated. This system has been described in this JOURNAL (*15*). To show the color of the light given by the mercury arcs and how this color changes as the pressure of the vapor in the lamp is changed, the color coordinates of a number of mercury arcs from the low-pressure (Cooper Hewitt) arc up to the 1000-

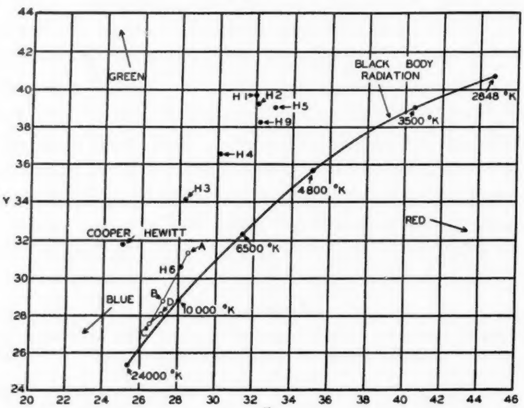

FIG. 20. I. C. I. color coördinates for a number of mercury lamps as shown and for the H-6 lamps operated at various pressures. Point A, 54 atmospheres; Point B, 156 atmospheres; Point C, 197 atmospheres; Point D, 319 atmospheres.

TABLE 5

Comparison of energy radiaated in the ultraviolet, visible and infrared portions of the spectrum by a 1000-watt quartz water-cooled mercury lamp and a 1000-watt high efficiency biplane-filament lamp

(For the Tungsten Lamp the Figures are for Energy Radiated Beyond the Bulb)

	1000-WATT BIPLANE AT 27.5 LPW	1000-WATT WATER-COOLED MERCURY IN #774 PYREX JACKET
Ultraviolet (3000–3800Å)	1.4 watts	66 watts
Visible (3800–7600Å)	150 watts	276 watts
Infrared (7600–inf)	790 watts	71 watts
Total watts radiated	941 watts	413 watts
Lumens	27,500 lumens	65,000 lumens

watt water-cooled mercury arc, and the variation in color of the H-6 lamp with pressure, have been plotted on an enlarged section of this diagram, Figure 20. It is to be noted that the light from the high-pressure lamp is not far from that of the blackbody curve. Indeed the light of some high-pressure mercury lamps that we have measured has coordinates that fit almost exactly a blackbody curve and indicates a color the same as that of a blackbody at a temperature of 12500°K.

TABLE 6

Intensities of principal lines of wavelengths less than 3135Å on the reflector axis for several ultraviolet sources

(Microwatts per cm² 30 inches from source)

SOURCE	S-1 UNIT*	S-2 UNIT*	S-4 UNIT†	G-1 UNIT*	G-5 UNIT*	TYPE RS LAMP‡	TYPE RS-4 LAMP‡
Volts	12.3	11.4	124	15	15.8	115	110
Amperes	29	9.0	0.90	2.2	5.0	2.4	0.95
WAVELENGTH							
2804	1.8	0.6	1.8	0.013	0.106	0.23	1.44
2894	3.3	1.0	5.4	0.16	0.62	1.46	2.7
2925			3.9		0.102	1.14	1.88
2967	16.1	4.2	25	0.63	2.4	11.6	12.7
3022	39	8.2	48	0.63	1.46	35	24
3129	187	33	136	6.7	14.0	120	71

* Reflector axis 30°.
† Reflector axis vertical.
‡ Reflector axis horizontal.

TABLE 7

Intensities of principal lines of wavelengths less than 3135Å from various ultraviolet sources

LAMP	S-1†	S-1*	S-2†	S-4*	G-1†	G-5†	D.C. UVIARC FOR 110 VOLT LINE	360-WATT T-6 UVIARC
Bulb glass	776	776	776	721	776	982	Quartz	Quartz
Volts	11.8	12.1	11.3	140	14.6	17.4	75	142
Amperes	29	29	9.0	0.83	2.2	5.0	3.75	2.90
WAVELENGTH	MILLIWATTS PER STERADIAN PERPENDICULAR TO ARC AXIS							
2537	0.04	0.16	0.03	0.00	0.01	0.04	320	475
2652	0.47	1.7	0.20	0.01	0.005	0.17	235	330
2804	1.2	4.6	0.57	1.7	0.02	0.25	110	155
2894	2.6	5.6	0.86	4.8	0.24	1.72	57	83
2925	0.92	2.1	0.28	3.4	0.04	0.22	19	33
2967	14.6	26	4.4	26	1.08	4.2	156	210
3022	27.7	61	7.6	48	0.79	2.6	315	395
3129	118	190	34	147	9.6	24	710	850

* Lamp axis vertical.
† Lamp axis at angle of 30° from vertical.

TABLE 8

Axial intensities of ultraviolet effective in producing erythema and total flux of this radiation within a 22" circle centered about this axis, at a distance of 30" from the center of the lamp, for various sources

SOURCE	MICROWATTS PER CM.² OF WAVELENGTH LESS THAN 3135Å	ERYTHEMAL ULTRAVIOLET	
		E-Vitons per cm.²	E-Vitons in 22" circle
Sun	91	2.0	4900
S-1 unit*	250	4.4	7000
S-2 unit*	47	1.0	1570
S-4 unit	220	6.0	8000
RS-4 lamp	117	3.1	6100
RS lamp	170	3.6	5900
G-5 unit*	29	0.57	1160
G-1 unit*	7.4	0.14	260

* Unit tilted 30° from vertical.

It is interesting to compare the energy radiated in the ultraviolet, visible, and infrared part of the spectrum by the 1000-watt quartz, water-cooled mercury lamp and a 1000-watt high efficiency (27.5 L/W) biplane, tungsten-filament incandescent lamp, Table 5. It is to be noted that this mercury arc radiates less than one-half as much wattage as this high intensity tungsten lamp and gives more than twice as much light. Thus the light from the mercury arc is much cooler than for the tungsten lamp. For the same amount of light, the tungsten lamp radiates about five times as much energy as the mercury arc. This advantage is due in part to the amount of energy that is carried away from the mercury arc by the flowing water.

MERCURY ARC SUN LAMPS

Tungsten mercury arcs are used as the Mazda S-1 and S-2 sun lamps. The arrangement of the tungsten electrodes, filaments, etc. is shown in Figure 7. These lamps are to be operated with the base up and the lamp in a position not too far from vertical, so that the hot filament and electrodes will keep the mercury in the bulb at such a temperature that it will supply the necessary pressure of mercury vapor for the proper operation of the lamp. The S-1 lamp consumes about 400 watts while the smaller lamp, designated as the S-2 lamp, consumes about 130 watts.

A low-pressure mercury arc that is sometimes referred to as a mercury glow lamp has been used as a special type of sun lamp. Two lamps of this type are offered, the G-1 and the G-5. The G-1 consumes overall about 50 watts and the G-5 consumes about 120 watts.

A lamp of the high-pressure type is now listed as the S-4 sun lamp. This is the H-4 mercury arc lamp mounted in a bulb that transmitts radiation in the therapeutic region. Some of the characteristics of various ultraviolet sources are given in Table 6, and of sun lamps in Tables 7 and 8.

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VOLUME 25

VOLUME 26

VOLUME 27

VOLUME 28

VOLUME 29

VOLUME 30

VOLUME 31

VOLUME 32

VOLUME 33

VOLUME 34

VOLUME 35

VOLUME 36

VOLUME 37